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Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems

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A B S T R A C T

This paper aims to examine the sustainability and environmental performance of PV-based electricity generation systems by conducting a thorough review of the life cycle assessment (LCA) studies of five common photovoltaic (PV) systems, i.e., mono-crystalline (mono-Si), multi-crystalline (multi-Si), amorphous silicon (a-Si), CdTe thin film (CdTe) and CIS thin film (CIS), and some advanced PV systems. The results show that, among the five common PV systems, the CdTe PV system presents the best environmental performance in terms of energy payback time (EPBT) and greenhouse gases (GHG) emission rate due to its low life-cycle energy requirement and relatively high conversion efficiency. Meanwhile, the mono-Si PV system demonstrates the worst because of its high energy intensity during the solar cells' production process. The EPBT and GHG emission rate of thin film PV systems are within the range of 0.75–3.5 years and 10.5–50 g CO_2-eq./kW h, respectively. In general, the EPBT of mono-Si PV systems range from 1.7 to 2.7 years with GHG emission rate from 29 to 45 g CO_2-eq./kW h, which is an order of magnitude smaller than that of fossil-based electricity. This paper also reviews the EPBT and GHG emission rates of some advanced PV systems, such as high-concentration, heterojunction and dye-sensitized technologies. The EBPT of high-concentration PV system is lower, ranging from 0.7 to 2.0 years, but the CO_2 emission rate of dye-sensitized PV system is higher than the ones of other PV systems at the moment. The LCA results show that PV technologies are already proved to be very sustainable and environmental-friendly in the state of the art. With the emerging of new manufacturing technologies, the environmental performance of PV technologies is expected to be further improved in the near future. In addition, considering the existing limitations in the previous LCA studies, a few suggestions are recommended.

Contents

Abbreviations: a-Si, amorphous silicon; BIPV, building integrated photovoltaic; BOS, balance of system; CdTe, cadmium telluride thin film; CIS, copper indium selenide thin film; EG-silicon, electronic silicon; EPBT, energy payback time; EVA, ethyl-vinyl acetate; EYR, energy yield ratio; GHG, greenhouse gases; GWP, global warming potential; hcPV, high-concentration photovoltaic; LCA, life cycle assessment; LCI, life cycle inventory; MG-silicon, metallurgical grade silicon; MOCVD, metallorganic chemical vapor deposition; Mono-Si, mono-crystalline silicon; multi-Si, multi-crystalline silicon; PV, photovoltaic; SoG-silicon, solar-grade silicon; TCO, transparent conducting oxide

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1. Introduction

With the population growth and economic development, humans need more and more energy to create a better living environment. However, the burning of traditional fossil fuels can cause a series of serious environmental problems, such as climate change, global warming, air pollution, acid rain and so on. Therefore, there is urgent need for developing renewable energy technologies, especially photovoltaic (PV), to cope with the challenges of energy shortage and environmental pollution [1].

Generally speaking, PV technology, directly generating electricity from solar energy, is free from fossil energy consumption and greenhouse gases (GHG) emission during its operations. Thus, it seems to be completely clean and have no environmental impacts. However, during its life cycle, it actually consumes a large amount of energy and emits some GHG during some stages such as solar cells manufacturing processes, PV module assembly, balance of system (BOS) production, material transportation, PV system installation and retrofitting, and system disposal or recycling. In order to accurately investigate the environmental performance of PV systems, life cycle assessment (LCA) is usually conducted to evaluate their environmental impacts during life cycle. The two most widely-used environmental indicators, energy payback time (EPBT) and greenhouse gases (GHG) emission rate, can be used to easily evaluate the sustainability and environmental performance of PV systems.

Life cycle assessment (LCA) is usually used as a technique to compare and analyze the energy using and environmental impacts associated with the development of products over their life-cycle. The whole LCA usually consists of four stages, viz. goal and scope definition, inventory analysis, impact assessment and interpretation. The framework of LCA methodology is shown in Fig. 1 [2–7]. The function of goal and scope definition is to determine the research objective and the system's boundaries. The work of inventory analysis mainly focuses on analyzing and recording the flows of pollutants, materials and resources throughout the life-cycle. In the stage of impact assessment, the energy consumption, resource consumption and various pollutions emissions will be presented, categorized and cumulated for different environmental problems such as global warming potential, acidification potential, ozone layer depletion, ecotoxicity, etc. Lastly, the final conclusions of LCA for this specific product will be drawn in the stage of interpretation [6,7]. With the final conclusions we can find the improvement potential to reduce its negative impacts on environment, natural resource and human health. Nowadays, the LCA method has been widely using to evaluate and compare the energy benefits and environmental performance of different new energy technologies, such as photovoltaic, wind power, nuclear power and so on.

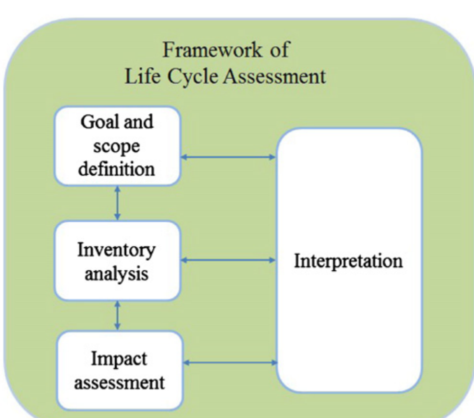


Fig. 1. Framework of life cycle assessment methodology.

The EPBT indicator is defined as the years required for a PV system to generate a certain amount of energy (converted into equivalent primary energy) for compensation of the energy consumption over its life cycle, including energy requirements in PV modules' manufacturing, assembly, transportation, system installation, operation and maintenance, and system decommissioning or recycling [8]. The calculation equation of EPBT can be usually presented as Eq. (1):

$$\mathrm{EPBT} = \frac{E_{\mathrm{input}} + E_{\mathrm{BOS},E}}{E_{\mathrm{output}}} \tag{1}$$

where, E_{input} is the primary energy input of PV module during life cycle, which including energy requirements in module manufacturing, transportation, installation, operation and maintenance, and module decommissioning or recycling, (MJ); $E_{\mathrm{BOS},E}$ is the energy requirement of the balance of system (BOS) components, which including support structures, cabling, electronic and electrical components, inverters, and batteries (for stand-alone system), (MJ); E_{output} is the annual primary energy savings due to electricity generation by PV system, (MJ).

As the EPBT of a PV system is defined as the energy requirements of PV modules and BOS components divided by its annual energy output, thus it is determined by a number of factors such as type of PV module, manufacture technologies, module conversion efficiency, installation location (facade or roof-top or ground mounted) and pattern (integrated or mounted), array support structure, frame or frameless, application type (stand-alone or grid-connected) and performance ratio (all losses included) [9]. EPBT is regarded as a perfect evaluation indicator for sustainability, through it we can clearly find out whether the specific PV system can bring a net gain of energy for user during its life time and if so to what extent.

Compared with the traditional fossil-based power plants, one important merit of PV power systems is the potential to mitigate GHG emissions. For example, PV system could eliminate up to 1000 t of CO_2, 10 t of SO_2, 4 t of NOx and 0.7 t of particulate matters by generating per GW h of electricity [10]. Meier and Kulcinski [11] conducted a life-cycle assessment on GHG emission of a building-integrated PV system, which using amorphous thin film PV modules with conversion efficiency of 6%. The results showed that the PV system would only emit 39 t of CO_2-equivalent (CO_2-eq.) for generating every GW h of electricity

Nomenclature

Subscript

E_{input}	primary energy input during life cycle
$E_{BOS,E}$	energy requirement of the balance of system
E_{output}	annual electricity generation of PV system
$GHG_{e\text{-rate}}$	GHG emission rate of unit electricity power generated by PV system
$GHG_{e\text{-total}}$	total amount of GHG emission throughout the life cycle
$E_{LCA\text{-output}}$	total electricity power generated by PV system during its life cycle
GHG_{PV}	GHG emission of PV modules
GHG_{BOS}	GHG emission of BOS components

under the solar insolation of 1934 kW h/m^2/yr, which was far less than that of conventional coal-fired plants.

Although the best-known GHG is carbon dioxide (CO_2), many other gases, such as SO_2, NO_x, CH_4 etc., are also remarkable greenhouse gases. The greenhouse effect of a specific gas is usually defined as its global warming potential (GWP) relative to CO_2,[1] therefore it can be expressed as a CO_2-equivalent amount for convenience [9,12]. To facilitate the comparing and evaluating the environmental impacts of different power generation technologies, a useful indicator of GHG emission rate can be introduced to measure the sustainability and ‘‘greenness’’ of different power generation systems. GHG emission rate denotes that how many greenhouse gases would emit while per unit of electricity power is generated. For PV power systems, the GHG emission rate can be expressed as the total GHG emissions of PV system (including BOS) divided by the generated electricity amount during its life cycle. Eq. (2) shows how to calculate the GHG emission rate of a specific PV system.

$$GHG_{e\text{-rate}} = \frac{GHG_{e\text{-total}}}{E_{LCA\text{-output}}} = \frac{GHG_{PV} + GHG_{BOS}}{E_{LCA\text{-output}}} \quad (2)$$

where, $GHG_{e\text{-rate}}$ is the GHG emission rate of per unit electricity power generated by PV system (g CO_2-eq./kW h); $GHG_{e\text{-total}}$ is the total amount of GHG emission throughout the life cycle (g CO_2-eq.); $E_{LCA\text{-output}}$ is the total electricity power generated by PV system during its life cycle (kW h); GHG_{PV} and GHG_{BOS} are the total GHG emission with respect to PV modules and BOS components, respectively.

This papers aims to fully investigate the energy payback performance and the environmental impacts of solar PV systems by conducting a thorough review on their EPBT and GHG emission rate. The life cycle assessment is conducted for five types of common PV systems, i.e., mono-crystalline (mono-Si), multi-crystalline (multi-Si), amorphous silicon (a-Si), cadmium telluride thin film (CdTe) and copper indium gallium selenide thin film (CIS). The EPBT of other PV systems including high-concentration and dye-sensitized are also discussed for comparisons. Lastly, some new technologies/measures and their effects on the EPBT and GHG emission rate are presented and discussed.

2. Life cycle assessment for PV systems

Although PV system is widely recognized as one of the most cleanly technologies for power generation, some people argued that it consumes energy during its life cycle, particularly in the manufacture processes, which may be larger than its energy output in its whole life. Therefore, in order to thoroughly investigate the life-cycle environmental effects and energy payback performance of PV system, life cycle assessment is used to measure its sustainability.

The methodology guidelines for LCA study of PV systems was reported in [13,14]. These guidelines could be summarized into the following three points: first, the technical characteristics in terms of LCA of PV systems were recommended. Second, the modeling approaches for LCA of PV systems were specified. Lastly, the attention to reporting and communication were given. Alsema and Wild-Scholten [15] had collected the life cycle inventory (LCI) data for crystalline silicon modules (mono-Si, multi-Si and ribbon-Si) from a number of PV manufacturers. Compared with previous data and work, a major improvement of their work was the acquirement of a large amount of measured data from several sources. Meanwhile, the authors also pointed out the limitations of the existence of many uncertainties for mono-Si production, in particular the Czochralski process, due to the unavailability of the data from the manufacturers. Dones and Frischknecht [16] performed the LCA studies on mono-Si and multi-Si modules technologies in Switzerland. The detailed environmental inventories, such as material/energy requirements and emissions in every stage of life cycle for slanted-roof solar modules and large plants, were presented. This study presented useful information about energy requirements and GHG emissions in PV manufacturing chains and provided a solid foundation for future LCA research.

Jungbluth et al. [17,18] described the LCA study of the representative state-of-the-art PV power plants in Switzerland. A large amount of data from manufacturers and other researchers were used to update the Ecoinvent database for PV system. Sixteen different, grid-connected PV systems (including module types of panels or laminates, solar cell types of mono-Si or multi-Si, and installation types of facades, slanted or flat roof) were analyzed. Ito et al. [19] conducted the life cycle analysis on six types of PV modules with actual system data and operating data. During the whole life cycle of PV system, from mining stage to the disposal stage, the data of mining and manufacturing processes was taken from previous LCA database, and the other data such as the solar irradiation, electricity power output of PV system, transport distance, construction energy consumption and amounts of equipment, was obtained from the actual systems. The using of actual data could help to avoid the errors caused in estimating the energy requirement and energy yield of PV system, thus it is expected to obtain more accurate LCA results. In addition, the degradation ratio was also considered in this LCA study for calculating the lifetime energy yield. The degradation ratio of crystalline silicon modules and thin film modules are assumed to be 0.5%/yr and 1%/yr, respectively.

3. Life cycle energy requirement of PV systems

3.1. Manufacturing processes of crystalline silicon PV modules

The manufacturing processes of silicon-based PV modules (including mono-Si, multi-Si and a-Si) are illustrated in the Fig. 2, [6].

[1] All the GHG emissions emitted in the life cycle of PV system can be expressed as an equivalent of carbon dioxide (CO_2) by using the 100 years' time horizon, which based on the IPCC characterization factors for the direct GWP of air emissions.

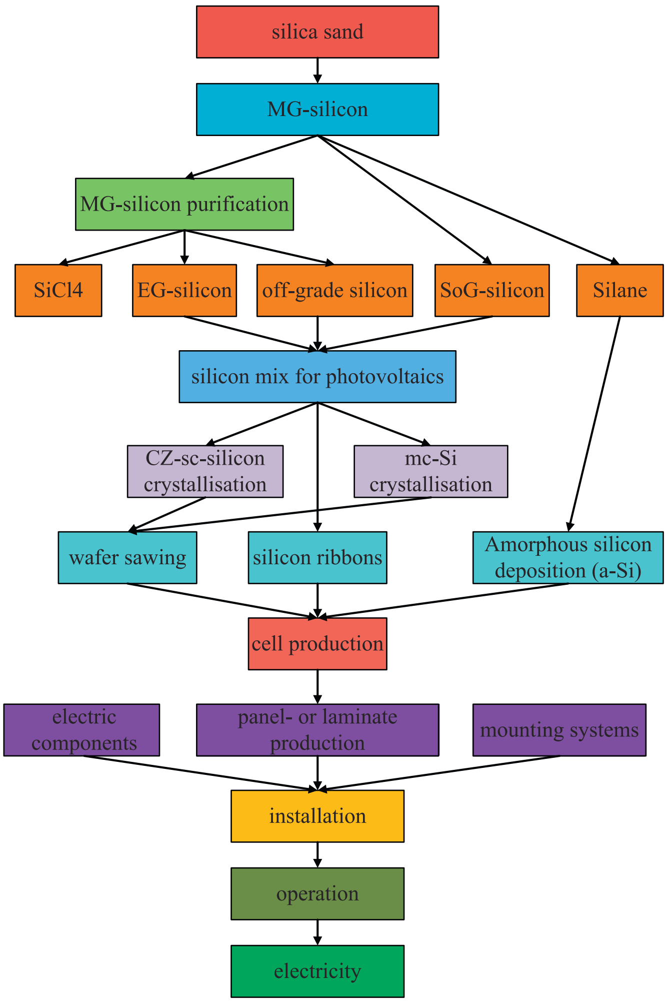


Fig. 2. The manufacturing processes of silicon-based PV modules.

The processes mainly include quartz reduction, metallurgical grade silicon (MG-silicon) purification, electronic silicon (EG-silicon) or solar-grade silicon (SoG-silicon) production, mono-Si or multi-Si crystallization, wafer sawing, cell production, and panel or laminate assembly [6]. Firstly, silica sand is put into an arc furnace for reducing so as to obtain impurity MG-silicon, and then the MG-silicon needs to be further purified into EG-silicon by Siemens process or purified into SoG-silicon by modified Siemens process or other processes. The Siemens process takes place in a reactor chamber in which the trichlorosilane ($SiHCl_3$) and hydrogen (H_2) gases are heated to 1100–1200 °C for reaction, while in the modified Siemens process the silane (SiH_4) and hydrogen (H_2) gases only need to be heated to about 800 °C. Thus, a lot of energy will be saved in the modified Siemens process [20,21]. Due to the fast growth of photovoltaic industry in recent years, the off-grade silicon from electronic industry can't meet the market demands, thus nowadays a large amount of silicon used in the PV industry is produced specifically with a modified Siemens process. The share of off-grade silicon has been decreasing in PV silicon supply chain, it was estimated that the off-grade silicon accounted for only 5% of total PV supply in 2006 and it would decrease further in future [22].

EG-silicon, off-grade silicon and SoG silicon compose the silicon mix for today's PV industry, these silicon feedstock will be molten and cast into molds. Multi-Si wafers can be directly produced from these polycrystalline blocks, while for mono-Si wafer production the Czochralski process is needed, which is to slowly extract the growing crystal from the melting pot. Then the silicon ingots will be cut by band saws or wire saws into columns with a cross section which is determined by the final wafer size [23]. Usually, the mono-Si columns are sawn into square wafers with a size of $156\times156\,mm^2$ ($0.0243\,m^2$) and an assumed thickness of 180–270 μm. The multi-Si columns are sawn into wafers with a square size of $156\times156\,mm^2$ and an assumed thickness of 180–240 μm [24–26]. After wafer sawing, the next step is cell production, and the main technologies of cell production are as follows:

1) Etching: the wafers are put into chemical baths to remove their surface microscopic damage and sawn parts.
2) Doping: after etching, a doping process has to be carried out on the wafers in order to create the photoactive PN junction. The common case is doping with phosphorous.
3) Screen printing: in order to collect electron, metallization is needed to print on the front and backside of wafer.
4) Coating: in order to increase irradiation and improve efficiency, the anti-reflection coating is painted on the front size.
5) Checking: the finished cell should be checked for the electrical characteristics as well as efficiency.

For PV panel or laminate manufacture, the cells are connected into string with silver contacts in the front and the back sides firstly, and then the solar cells are embedded into the two layers of ethyl-vinyl acetate (EVA) (one each for the front and the back side, respectively) which is used to provide protection from the physical elements during operation. On the front side of EVA, a 1 to 3 mm low-iron glass sheet is added to the front cover, and a Tedlar film is used as the rear cover on the back side. The sandwich-type panel is then molded under pressure and heat machine, the edges are purified, and the connections are insulated [23,27]. For PV panel manufacture, the additional aluminum frame is needed for strengthening and easy mounting, while for PV laminate the frame is needless, it can be directly integrated into building. Finally, panels and laminates are tested and packed.

3.2. Manufacturing processes of thin film PV modules

For the thin film technologies (CdTe and CIS), the photoactive P/N junction consists of two semiconductor compounds, CdTe or CuInSe2 and CdS, which are directly deposited in the extremely thin layers on a cleaned substrate glass by means of a vacuum vaporisation process. Series connection of adjacent P/N junctions is achieved by means of a series of automated laser and mechanical scribing processes, and then a second protective glass pane is added on top to form the finished module [28]. The flow chart of the production of thin film PV modules is shown in Fig. 3, [23].

Kato et al. [29] briefly described the production processes of CdTe as follows: first, a transparent conducting oxide (TCO)-layer will be deposited on a cleaned substrate glass. Then the CdS-layer with organic cadmium compound is deposited on the TCO-layer by metallorganic chemical vapor deposition (MOCVD). After grooves have been produced on the CdS-layer by a laser, CdTe-layer is formed by using the atmospheric pressure close spaced sublimation technique. This process is followed by a thermal treatment carried out with $CdCl_2$, and then mechanical patterning is done. Finally, CdS/CdTe solar cell is completed by screen printing with both carbon and silver contacts.

3.3. Life cycle energy requirement of PV modules

3.3.1. Energy requirement of crystalline silicon PV modules

Since before 1990s then the PV industry just started to develop, some scholars already began to investigate the energy

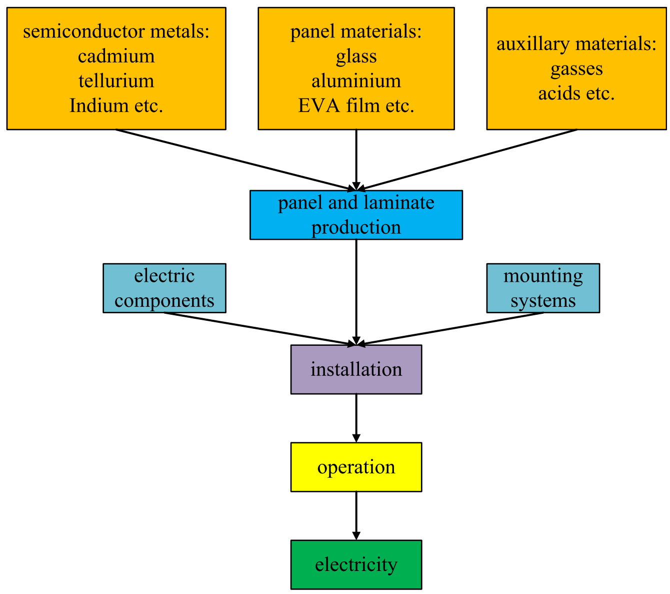


Fig. 3. The flow chart of the production of thin film PV modules.

requirement of crystalline silicon PV system to evaluate its sustainability. As early as 1976, Hunt [30] estimated the total energy use for manufacturing silicon solar cells from raw materials of SiO_2 and reported that with technology of that day, the energy payback times were 12 and 24 years for terrestrial cells and space cells, respectively. In 1990, an analysis of energy investment for producing PV modules in commercial production lines of France was conducted [31]. It was estimated that the average EPBTs of amorphous silicon modules and crystalline silicon modules were 1.2 and 2.1 years, respectively. However, it seems to not include the embodied energy of materials into the total energy requirement. The accumulated energy using in manufacturing PV modules and constructing PV plants as well as the corresponding GHG emissions were studied in detail [32]. Phylipsen and Alsema [33] studied the environmental assessment of multi-Si PV module in 1995. The embodied energy requirement for multi-Si module was found to be 1145 kW h_t/m^2 [2] (cell accounts for 970 kW h_t/m^2, while frame accounts for 175 kW h_t/m^2). The energy consumption for producing PV modules in manufacturing lines of India was analyzed [34]. It was found that the EPBT was approximately 4 years, which was comparable to EPBTs in other countries at that time.

Kato et al. [35] investigated the total energy requirement of crystalline silicon PV modules with different energy allocation cases for silicon wafer production. The results showed that just by using different allocation methods the total energy requirement estimated for a mono-Si PV module can range from 4160 to 15520 MJ/m^2. The total energy requirement based on mass allocation, which was regarded as the best method in their cases, was about 11670 MJ/m^2. Alsema et al. [36] reviewed many previous studies on energy analysis and established a "best estimate" condition for evaluating embodied energy requirement of mono-Si and multi-Si modules. For crystalline silicon modules, the main uncertainty of energy requirement was the preparation of silicon feedstock. Thus, according to different preparation methods for silicon feedstock, a low and a high estimates were presented for evaluating mono-Si and multi-Si PV modules' energy requirements. Considering that standard electronic-grade silicon would be too expensive and may not be sufficient for PV applications, dedicated silicon purification routes would be needed, and thus the lower energy estimate was probably more representative than the higher one for near-future technology. With the low estimate condition, the energy requirements for mono-Si and multi-Si modules were 6000 and 4200 MJ/m^2, respectively. There were considerable differences in the energy requirement of crystalline silicon PV modules in the estimates published previously, viz. varying from 2400 to 7600 MJ/m^2 for multi-Si modules and 5300 to 16,500 MJ/m^2 for mono-Si modules [37]. These differences may be caused partly by different process parameters such as wafer thickness and wafering loss. However, the main source of the differences was stemmed from the energy estimation for silicon purification and crystallization processes. After ignoring the specifically needed process steps for the microelectronics wafer production and using the lower estimates for process energy consumption, it was estimated that the total energy requirements of multi-Si and mono-Si frameless modules were 4200 and 5700 MJ/m^2, respectively. Although mono-Si module possesses higher conversion efficiency, it was at a slight disadvantage compared with multi-Si module due to its higher energy intensity in crystallization process.

Knapp and Jester [38,39] conducted an empirical investigation on PV modules' production to estimate process energy and materials' embodied energy by utilizing measured energy use, actual utility bills, production data and complete bill of materials. The total process energy of mono-Si and CIS was 2742 and 1725 kW h_e[3]/kW$_p$, respectively, and the corresponding embodied energy of materials was 2857 and 1345 kW h_e/kW$_p$, respectively. The embodied energy for the production of the crystalline silicon PV module and BOS components was also analyzed in [40]. The evaluated results showed that the embodied energy for open filed and roof-top PV systems was 1710 and 1380 kW h_e/m^2 respectively, and the EBPT was in the range of 7–26 years accordingly. The results of both embodied energy and EBPT are very high, which deviate from the previous research results too much.

Tables 1 and 2 present the results of previous energy requirement breakdowns for mono-Si and multi-Si PV module, respectively. It is found that, the energy requirement of per unit area of crystalline silicon cell gradually decreased from higher than 10000 MJ$_p$/m^2 in 1990s to less than 3000 MJ$_p$/m^2 in 2010 with the rapid growth of PV industry and the continuous improvement of cell production technologies. The main reasons contributed to the reduction are summarized as below:

1) the enhancement of usage efficiency of silicon material, including reducing the wafer thickness and decreasing the silicon loss in the wafering process;
2) new crystallization processes which can reduce the energy consumption for producing mono-Si;
3) replacing the standard electronic-grade silicon purification process with dedicated silicon purification process for PV industry, which results in lower purity as well as lower energy consumption;
4) recycling and reusing of silicon material.

3.3.2. *Energy requirement of thin film PV Modules*

In the early commercialization stage of crystalline silicon solar cell, the high cell cost and large energy consumption in its production process impeded its large-scale commercialization. To solve this cost barrier, researchers started focus on developing more cost-effective and lower energy consumption thin-film PV modules. Compared with crystalline silicon solar cell, the production of thin-film solar cell requires much less material

[2] kW h_t means one kilowatts hour thermal energy.

[3] kW h_e means one kilowatts hour electricity power.

Table 1
Energy breakdown for manufacturing mono-Si PV module.

Authors/years	MG-silicon (MJ_p/m^2)	Si feedstock (MJ_p/m^2)	CZ of mono-Si (MJ_p/m^2)	Wafer (MJ_p/m^2)	Cell production (MJ_p/m^2)	Module assembly (MJ_p/m^2)	Frame (MJ_p/m^2)	Total (MJ_p/m^2)	Remark
Kato and Murata [35]	298	797	9808		261	509	N/A	11673	The $SiCl_4$ was dealt with as a by-product
Alsema and Frankl [36]	500	1900	2400	250	600	350	Frameless	6000	Low energy estimate
Alsema [37]	450	1800	2300	250	550	350	Frameless	5700[a]	
Knapp and Jester [38]	3950 MJ/m^2 (Converted by2742 kW h_e/kW_p)		4100 MJ/m^2 (Converted by 2856 kW h_e/kW_p)				N/A	8050[b]	
Alsema and Wild-Scholten [15]	1759		2391		473	394	Frame (236)	5253	Wafer thickness 285 μm
Jungbluth and Stucki [23]	141	888	1208	562	595	466	Frame	3860	
Wild-Scholten [41]	728		1266		389	477	Frameless	2860	
Laleman [42]	2397		432			684		3513	

[a] Disregard process steps are specifically needed for the micro-electronics wafers and the lower estimate for process energy is employed.
[b] 8050 MJ/m^2 is converted in terms of 5598 kW h/kW$_p$.

Table 2
Energy breakdown for manufacturing multi-Si PV module.

Authors/years	Si feedstock production (MJ_p/m^2)	Casting, cutting, wafer process (MJ_p/m^2)	Cell production process (MJ_p/m^2)	Module assembly process (MJ_p/m^2)	Frame (MJ_p/m^2)	Others (MJ_p/m^2)	Total (MJ_p/m^2)	Remark
Kato and Murata [35]	1562	717	353	709	N/A	39	3380	30 MW/ year
Alsema and Frankl [36]	2250	1000	600	350	Frameless	N/A	4200	Low energy estimate
Alsema and Nieuwlaar [43]	2200	1000	300	200	Frame (400)	500[a]	4600	
Battisti and Corrado [44]	3904	535	115	556	N/A	40	5150	The Si feedstock come from EG silicon scraps[b]
Alsema and Wild-Scholten [15]	1759	1078	473	276	Frame (236)	118	3940	
Pacca and Sivaraman [45]	1075		3247		N/A	N/A	4322	
Alsema and Wild-Scholten [46]	1400	550	400	500	Frame (270)	N/A	3120	
Jungbluth and Stucki [23]	1030	968	544	523	Frame	N/A	3065	
Wild-Scholten [41]	1110	744	378	467	Frameless	N/A	2699	

[a] This energy was for overhead operation and equipment manufacture, such as lighting, climatization of the module production plants, and environmental control.
[b] The impact allocation between electronic industry outputs, i.e., primary products and byproducts as electronic scraps, has been performed on a mass basis. This means that 1 kg of silicon scraps is considered to have the same 'environmental responsibility' as 1 kg of silicon contained in electronic end products.

with much lower cost. The production process is relatively simple without high-temperature process, thus the process consumes much lower energy.

Lewis and Keoleian [47,48] conducted a case study on producing of amorphous silicon PV modules in United Solar with life cycle design. The energy requirements for producing product materials and manufacturing process were analyzed in detail. The total process energy was about 491 MJ/m^2. While there were low case and high case for estimating the embodied energy in product materials, and they were 864 and 1990 MJ/m^2, respectively. However, if the frame was omitted, the above embodied energy would be sharply reduced to 386 and 640 MJ/m^2, respectively. It can be seen that the aluminum frame would significantly increase the energy requirement of a-Si thin film PV module. Thus the authors recommended that it was very helpful for reducing the energy requirement by reusing frame or designing frameless modules. In addition, the EPBT was also reported. Depending on the solar radiation level and the cases of embodied energy, the EPBT of a-Si PV module with 5% efficient ranged from 2.3 to 13 years. The authors also investigated the effect of module's efficient on the EPBT and presented that if the efficient increased to 8%, the EPBT would corresponding reduce to 1.4–8.1 years. The embodied energy of a frameless a-Si module was estimated to vary from 710 to 1980 MJ/ m^2 in 1998 [36]. The considerable differences were explained by the different utilizations of substrates and/or encapsulation materials, and whether the energy requirement for manufacturing the production equipment is considered or not.

A life cycle energy analysis on a-Si PV module was presented in [49]. Three metrics, viz. life-cycle conversion efficiency, electricity

production efficiency and energy payback time, were defined to comprehensively evaluate the life cycle energy performance of PV systems as well as guide the development of PV technology. The total energy requirement for framed PV module was about 1458 MJ/m^2, which including the embodied energy of materials, process energy, transportation energy and so on. While the energy requirement for frameless PV module was only about 894 MJ/m^2. The impact of conversion efficiency on the EPBT was also studied and the results showed that with the conversion efficiency increasing from 5% to 9%, the EPBT of framed a-Si PV system would range from 7.4 to 4.1 years under the solar insolation of 1202 kW h/m^2/yr. However, the corresponding EPBT of frameless a-Si PV system ranged from 4.6 to 2.5 years, which was almost half of that of framed module PV system.

Alsema [50] conducted the energy analysis studies of thin film PV modules. After reviewing and analyzing the results from six outstanding studies on a-Si modules and three studies on CdTe module, the author presented the best estimate for the energy requirement of a-Si and CdTe thin film frameless modules at that time, which was between 600 and 1500 MJ/m^2. The difference of energy requirement was caused by the different types of cells and their encapsulations. Kato et al. [29] estimated that the total primary energy requirement for producing 1 m^2 of the CdS/CdTe PV module was around 1803 MJ/m^2 at 10 MW/yr production scale, 1514 MJ/m^2 at 30 MW/yr and 1272 MJ/m^2 at 100 MW/yr. Although the total primary energy requirement was approximately equivalent to a-Si module, the production of CdS/CdTe PV modules needed more direct process energy and less material embodied energy compared with the production process of a-Si PV module. Therefore, CdS/CdTe solar cells and a-Si solar cells seem to be direct-energy intensive and material-energy intensive, respectively.

The gross energy demands of CIS and CdTe laminates were reported to be 27,700 and 7,600 MJ/kW$_p$, respectively in [28]. By considering the BOS components' energy requirement, the corresponding total gross energy demands would sharply increase to 39,400 and 21,900 MJ/kW$_p$, which indicated that the BOS components might have a significant effect on the thin film PV systems comparing with the modules themselves. For large-scale PV plants, the energy requirements were estimated to be 1069 MJ/m^2 for CIS, 918 MJ/m^2 for CdTe, 1202 MJ/m^2 for a-Si and 2044 MJ/m^2 for multi-Si module, respectively [51]. Alsema [37] concluded that the energy requirement differences of a-Si thin film modules in previous publications were mainly due to the selection of substrates and/or encapsulation materials, as well as the energy requirement for manufacturing the production equipment. If using a polymer cover to replace glass encapsulation could save energy requirement by 150 MJ/m^2. On the contrary, adding an extra substrate layer may increase the energy input by 150 MJ/m^2. Based on the comparisons and analysis of published energy estimates, the author gave the best estimate for energy requirement of a-Si thin film module, which was about 1200 MJ/m^2 and was expected to be reduced to 900 MJ/m^2 before 2010.

The previous LCA estimated results for thin-film PV modules are collected in Table 3. Among the three types of common thin film PV modules, the CIS module consumes the most energy while the CdTe module consumes the least. Compared with crystalline silicon solar cell, the total energy requirement of thin film PV modules is reduced significantly. For thin film PV modules, the energy consumption can be almost classified into two categories, viz. direct process energy and material embodied energy. With the improvement of production technology, there are still spaces to reduce the direct process energy in future, but it is difficult to further reduce the material embodied energy unless cheaper and easily available substrate and encapsulation materials can be developed. It is noteworthy that the frame would add about 15–25% energy to the total energy demand of thin film modules,

Table 3
Energy breakdown for manufacturing thin-film PV modules.

Authors/years	Solar cell	Cell material (MJ_p/m^2)	Substrate + encapsulation materials + Cell production (MJ_p/m^2)	Process energy (MJ_p/m^2)	Capital equipment (MJ_p/m^2)	Module assembly (MJ_p/m^2)	Frame (MJ_p/m^2)	BOS (MJ_p/m^2)	Total (MJ_p/m^2)
Kato and Murata [35]	a-Si	1078		449			Frame	N/A	1587
Alsema and Frankl [36]	a-Si	400		400			Frameless (300–770)	400	1200
Alsema [50]	a-Si	40	300–400 (two glass sheets) 170–250 (glass/polymer)	500–840	100–200	N/A	Frameless frame (50–500)	N/A	940–1480 (frameless)
Alsema [50]	CdTe	40	300–400 (two glass sheets) 170–250 (glass/polymer)	350–650	100–200	N/A	Frameless frame (50–500)	N/A	790–1270 (frameless)
Alsema and Nieuwlaar [43]	a-Si	50	350	400	N/A	N/A	Frame (400)	400 (overhead operation and equipment manuf.)	1600
Knapp and Jester [38]	CIS	1380 (converted by 1345 kW h_e/kW_p)		1770 (converted by 1725 kW h_e/kW_p)		N/A	Frameless	N/A	3150[a]
Kato and Hibino [29]	CdS/CdTe	N/A	159	637	N/A	310	Frame (280)	128 (overhead)	1514
Pacca and Sivaraman [45]	a-Si	172	690				N/A	N/A	862
Wild-Scholten [41]	a-Si	50	350	400	189		Frameless	N/A	989
Wild-Scholten [41]	CdTe	40	244	400	127		Frameless	N/A	811
Wild-Scholten [41]	CIS	50	389	1245			Frameless	N/A	1684

[a] 3150 MJ/m^2 is converted from 3070 kW h_e/kW_p.

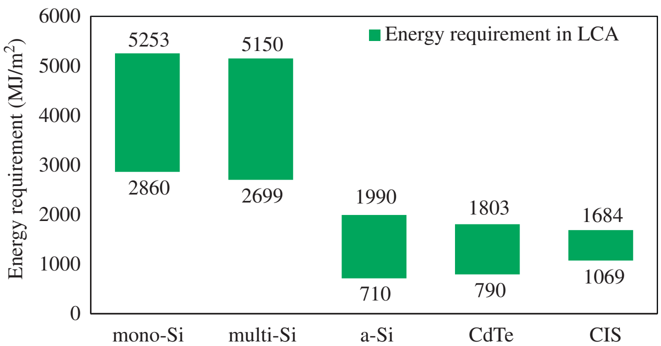


Fig. 4. Review of energy requirements during life cycle for various PV systems.

thus the frameless design is especially important for reducing the total energy requirement of thin film PV modules.

In order to have a more intuitive comparison of energy requirements between different PV technologies, the typical results of energy requirements in previous work are summarized and compared in Fig. 4. It is worth noting that because there is no dedicated silicon purification process to manufacture silicon feedstock for PV industry before 2005, and it is also found that the different energy allocation cases for silicon wafer production resulted in a large difference in energy requirement in early work. Therefore, for crystalline silicon PV modules, only the results after 2005 are adopted in this figure. It is obvious that the life cycle energy requirements of thin film PV systems are far less than that of crystalline silicon PV systems.

3.4. Energy requirement of BOS components

Usually, in a PV power generation system, besides the PV modules, the rest component parts are generally defined as the terms of balance of system (BOS) which includes inverter, controller, junction box, cabling, array support, battery, etc. Therefore, in order to obtain the total energy requirement of PV system throughout its life time, we also need to know the energy requirement of BOS components.

Alsema et al. [36] investigated the energy consumption of BOS components in several applications such as on rooftops and building façades. The results showed that the BOS energy content of a ground field PV power plant was as high as 1900 MJ/m^2 due to the large amount of concrete and steel used for supporting structure, while it was only around 600 MJ/m^2 for building-integrated PV systems. In addition, the energy consumption of module's frame was significant due to the large amount of aluminum used in the frame, which was about 300–770 MJ/m^2. Actually, it was reported that the concrete foundation was worse than steel pile foundation from the view point of environmental impacts [19,52]. A thorough study on the energy requirements and GHG mitigation potential of PV systems was presented in [53]. It was expected that the energy requirements of multi-Si and mono-Si PV system may be reduced to 2600 and 3200 MJ/m^2, respectively, if improvements, such as dedicated silicon feedstock production, improving casting technology and reducing silicon using per unit area, was achieved. The energy requirement of BOS of grid-connected roof-top system and stand-alone system was also estimated. It was assumed that 3.5 and 2.5 kg aluminum are respectively consumed for fabricating per square meter of array support and module frame, thus the energy requirement for array support and module frame were estimated to 700 and 500 MJ/m^2, respectively. For stand-alone PV system, the battery is a key component and its energy requirement was estimated in the range of 0.6–1.2 MJ/Wh. The EPBT and GHG emission rate of stand-alone PV system were also studied and they are obviously worse than that of grid-connected PV system because so many battery sets are needed during life cycle. Although its GHG emission rate reached up to 0.25–0.4 kg CO_2-eq./kW h, it was still far better than that of diesel generator of 1.1 kg CO_2-eq./kW h. The energy requirement for array support of ground-mounted and rooftop PV systems were estimated to be 1800 and 700 MJ/m^2, respectively in [43]. It was obvious that rooftop installation has much better potential for low EPBT than ground-mounted installation due to less use of aluminum in the array support.

Mason et al. [54] estimated the energy content of the BOS components used in a 3.5 MW_p multi-Si PV plant. An innovative PV installation technology incorporating the weight of the PV modules themselves as an element of support was implemented in this plant, so that a large amount of concrete foundations and steel support structures were eliminated. Therefore, the evaluated embodied energy of the BOS components was as low as 542 MJ/m^2, which was reduced by 71% compared with that of a previous ground-mounted plant in Italy [36]. The BOS components used in a 33 kW roof-top PV system was investigated in [45]. It was found that the primary energy consumptions for the BOS, inverter, and installation were 18,100, 15,100 and 74,200 MJ, respectively. In other words, the life-cycle energy requirement of all BOS components was 242 MJ/m^2, which accounted for 13.8% of the total energy requirement of the PV system. It was also pointed out that when the additional inverters were used due to replacement, the energy requirement for BOS components would increase to 276–310 MJ/m^2. The direct and indirect energy consumption related to materials' transportation amounted to 59,400 MJ, which could be converted into 134 MJ/m^2.

Alsema and Wild-Scholten [55] estimated the energy consumption of inverter was 1930 MJ_p[4]/kW_p, which included one replacement in half-way of the life cycle of PV system. The energy consumed in array support and cabling was assumed to be 100 MJ_p/m^2, which might be underestimated. The life cycle GHG emissions of above items were 125 kg/kW_p and 6.1 kg/m^2, respectively. For the transportation energy consumption, Lewis and Keoleian [56] reported the total transportation energy requirement of a-Si PV module with or without frame, which were 62 and 43 MJ/m^2, respectively. In addition, Alsema [50] assumed that the transportation energy by lorry was 2–5 MJ/t/km and the weight of module was about 15 kg/m^2. The energy consumption associated with taking back & recycling was estimated by Wild-Scholten [41], which was 250, 240 and 150 MJ for mono-Si, multi-Si and CdTe PV systems, respectively. The energy requirement in terms of overhead operations and the manufacturing of the production equipment itself was estimated to be 500 MJ/m^2 [43].

The environmental performance of tracking and fixed PV systems was compared in terms of energy payback time [57]. For the tracking PV systems, more energy was required for the metallic supporting structure, foundations and wiring. Moreover, every year the tracking systems themselves would consume part of electricity, for example, 7–13 kW h/kW_p for double-axis tracker and 4 kW h/kW_p for horizontal North-South tracker. Although the tracking PV systems required more energy input, this higher energy requirement would be fully compensated by their improved power performance during the life cycle.

The energy breakdown of BOS components are concluded in Table 4. From Table 4, we can see that the item of array support consumed a large proportion of energy, which is closely related to the installation methods. Generally, the array support of ground filed PV system need much more energy requirement than that of BIPV system due to the usage of large amount of concrete and steel.

[4] MJ_p means one million joules primary energy.

Table 4
Energy breakdown of BOS components.

Authors/years	Array support + cabling (MJ_p/m^2)	Inverter (MJ_p/m^2)	Transportation (MJ_p/m^2)	Installation (MJ_p/m^2)	Overhead oper. and equipment manuf. (MJ_p/m^2)
Lewis and Keoleian [56]			43		
Alsema and Frankl [36]	600 (facade) 700 (roof integrated)	0.5 MJ/kW			400
Erik Alsema [50]			30–75		
Frankl and Masini [58]	1800 (ground mounted) 600 (building integrated)				
Alsema and Nieuwlaar [43]					500 (mono and multi) 400 (thin film)
Alsema and Wild-Scholten [15]	100	1930 MJ_p/kW_p			
Alsema and Wild-Scholten [46]	70	1300 MJ_p/kW_p			
Pacca and Sivaraman [45]	94	503 MJ_p/kW_p	134	34	N/A

4. Solar radiation and energy output

According to Eq. (1), to calculate the EPBT for a specific PV system, its energy output during life cycle should be estimated. Solar irradiation is one main determining factor in the energy output of PV systems. To facilitate the calculation, most previous literature studies about LCA analysis chose to employ the approximate annual values for local solar irradiation, such as 1700 kW h/m^2 for South Europe [28,33,59], 1000 kW h/m^2 for Central Europe, 1117 kW h/m^2 for Switzerland [18], 2017 kW h/m^2 for Gobi Desert of China [51], 1800 kW h/m^2 for U.S. [12], 1427 kW h/m^2 for Japan [35], 1530 kW h/m^2 for Italy [44], and so on. The approximate annual solar irradiation of a specific country or territory can also be found in NASA's website [60]. However, some studies introduced a series of models to simulate the hourly solar irradiation based on local weather data for more accurate estimation [61–68]. In addition, the calculation of solar irradiation during a specific period of time, such as a certain month or a certain season, is possible by using this kind of simulation models.

In terms of energy output, its calculation mostly based on empirical parameters, assumptions and simplifications, as follows:

i. **Application type**: either the stand-alone or the grid-connected. For stand-alone PV system, an energy storage system is needed.
ii. **Conversion efficiency**: the nominal energy conversion efficiencies for the analyzed PV modules were assumed.
iii. **Life time**: the expected life time for the analyzed PV modules was assumed. The life time of crystalline silicon PV modules was usually assumed to be 30 years [69–71], which was in line with what has been proven to be attainable for c-Si modules. The life time of thin film PV modules was generally assumed to be 20–25 years according to the warranty given by the manufacturers [45,72]. For large scale PV plant, the lifetime of inverters is set to 30 years with 10% replacement every 10 years [13,19]. For low capacity inverters, the life time of electronic components inside the inverter was usually set at 15 years [24,54,69], and the replacement of electronic components in inverter is needed after 15 years' operation.
iv. **Performance ratio:** the performance ratio for analyzed PV systems, including all losses generated in the inverter, cable and transformer, was assumed. The performance ratio was assumed to be 0.75 by Alsema and Wild-Scholten [55], 0.78 by Ito et al. [73] by considering the conditions and co-efficiency of temperature in Gobi Desert, 0.80 by Fthenakis and Kim [12], 0.81 in [74], and 0.835 according to the measurement at the grid connection side [75]. In the methodology guidelines on LCA of PV systems [13] it was recommended to use either site specific value or a default value, viz. 0.75 for roof-top PV systems and 0.8 for ground-mounted PV systems as the performance ratio [21,54].
v. **Electricity generation efficiency**: the average electricity generation efficiency (viz. the conversion efficiency from thermal energy to electricity) was assumed. The average conversion efficiency of US electricity was assumed to be 0.29 [12] and 0.33 [76] based on a U.S. average fuel mix and power-plant efficiency. Alsema and Wild-Scholten [69] took 0.31 as the overall conversion efficiency of Western-European continent electricity grid (UCTE region), while it was assumed to be 0.32 in [28].
vi. **GHG emissions rate:** the GHG emissions rate of local electricity of the PV module manufacturers and installation location was determined based on the local mixture of fuel types. The GHG emission rate of Western-European continent electricity grid (UCTE region) was assumed to be 0.48–0.53 kg CO_2-eq./kW h [69,77]. In addition, 0.671 kg CO_2-eq./kW h was reported for Hong Kong [68], 0.012 kg CO_2-eq./kW h for Norwegian electricity supply mixes [77]. The GHG emission rate of Norwegian electricity grid was very low, because in this country most electricity was generated by hydropower. In addition, the mixture of electricity production and the GHG emission rate of different countries can be found in [78].

With the solar irradiation and the above assumptions in terms of conversion efficiency, performance ratio etc., the annual energy output of PV systems can be calculated conveniently. However, it is noteworthy that the energy output calculated by the above empirical methods is not accurate and may deviate from the real power output too much. Actually, during the real operating process of PV modules, there will be different kinds of energy losses caused by the internal and external environment, e.g. the self-degradation of solar cells, the influence of cell temperature, the impact of orientation and tilted angle of PV modules, the obscuration of dust, the partial shadow, the spectral changes, the mismatch between PV modules and inverter, and so on. These power losses are the main reasons why the real energy output is far from the calculated energy output according to the empirical methods.

Therefore, how to accurately model and predict the energy yield of PV system is becoming a hot research topic in recent years. Based on the equivalent circuit of solar cell, De Soto et al. [79] developed a five-parameter model to predict the current–voltage (I–V) curve of four different solar cells under all operating conditions. The prediction results were compared with the experimental results, and good agreement was found for crystalline silicon solar cells.

However, for a-Si solar cell, this five-parameter model is lack of accuracy due to its shortage in considering the effect of light-induced degradation, spectral response and the recombination current of a-Si solar cell. Therefore, in order to accurately predict the energy yield of PV system and then accurately calculate the EPBT and GHG emission rate, energy rating model with high accuracy rather than the empirical methods is recommended for life cycle assessment of PV system in future work.

There were very few literatures, actually only found in [19] so far, using the actual energy yield to conduct the LCA study on PV systems. While these actual energy yield results covered only 1 year. Therefore, long period energy yield data is expected to be collected for preferably calculating the EPBT and GHG emission rate, especially for thin film PV modules whose degradation ratio has a big influence on the long-term energy yield.

5. EPBT and GHG emission rate of PV systems

Although there are no energy using and GHG emissions during PV systems' operation, a large amount of energy and GHG emissions would be consumed and emitted during their whole life time, especially in the production process. To address the issues regarding the environmental performance of PV systems which including EPBT, GHG emission, environmental life-cycle assessment and so on, an expert workshop was specially held in 1997 [80]. Various environmental issues encountered in whole life cycle of PV systems were identified, and recommendations and approaches were also presented in this workshop to ensure that the PV systems could generate power in an environmental sustainability way. Estimating the EPBT and GHG emission rate of PV systems in a specific region is very difficult, because it is affected by so many parameters, such as life cycle energy requirement, electricity mix of PV modules' place of origin, local irradiation, local weather conditions as well as systems' life time. Actually, most GHG emissions during the PV systems' life-cycle were related to the energy consumption [16]. Emissions unrelated to energy use were only found in steel and aluminum production (for the supports and frames) and in silica reduction (for silicon solar cells), but the total proportion is less than 10% [43].

A comparative study on the reduction effect of carbon dioxde for solar PV systems installed in different locations was conducted in [81]. Three cases (viz. A: solar PV modules were made in Japan but used in Indonesia, B: made in Japan and used in Japan, C: made in Indonesia and used in Indonesia.) were analyzed and compared. It was found that the case A had the best effect to reduce carbon dioxde, which was due to that on the one hand the PV modules' manufacturing country has relatively high efficiency in thermal power plant and thus the GHG emission caused by producing PV modules was less, on the other hand the PV modules' using country has better solar energy resources, which could made the same PV system generate more electricity power during its life time. Thus the authors suggested that it was essential to make cooperation between developed countries which have good technologies and developing countries which have better solar energy resources to eliminate carbon dioxde by PV technology in future.

The life-cycle GHG emissions rate for PV systems in the United States were reported to be 22–49 g CO_2-eq./kW h with the average irradiation of 1800 kW h/m^2/yr [82]. While the GHG emissions rate for the average PV electricity mix in Switzerland was estimated to be around 73 g CO_2-eq./kW h [83]. Jungbluth et al. [18] thoroughly investigated sixteen grid-connected PV systems with different solar cells and/or different installation locations. The results showed the EPBTs were in the range of 2.5–4.9 years with respect to the different types of PV systems with the irradiation of 1117 kW h/m^2/yr. It was also pointed out that the difference in EPBT was mainly caused by different factors such as types of installation, types of solar cells and types of PV modules. Moreover, for different installation methods, it is found that the EPBT for façade installation PV systems is the longest, which is about two times longer than that of the slanted-roof type. The EPBT for the flat-roof installation type is moderate. In addition, the GHG emissions rate of the average PV electricity mixes in different countries was also discussed, with results between 48 and 83 g CO_2-eq./kW h.

The EPBT and GHG emission rate of PV systems installed in regions with low solar irradiation were estimated in [42]. It was found that the EPBT of six different PV-technologies were all less than 5 years under an irradiation of 900–1000 kW h/m^2/yr and the GHG emission rate was about 80 g CO_2-eq./kW h with a lifetime of 30 years. The authors also pointed out that the PV systems' lifetime had an important effect on the GHG emission rate of PV generated electricity, for example if the lifetime is shorted to 20 years, the GHG emission rate of PV electricity power would increase to 120–130 g CO_2-eq./kW h. Ito et al. [73] estimated the energy requirements of six types of PV module, viz. mono-Si, multi-Si, a-Si/mono-Si, thin-film Si, CIS, and CdTe, which ranged from 30 to 42 TJ/MW. Among the studied six types of PV modules, the CIS module had the smallest energy requirement of 30TJ/MW, and the mono-Si had the highest. Accordingly, the CIS PV system possessed the shortest EPBT of 1.8 years, the mono-Si needed the longest EPBT of 2.5 years, and the EPBTs for other types ranged from 2.0 to 2.3 years. The GHG emissions rates were from 43 to 54 g CO_2-eq./kW h. The PV plants with multi-Si solar cells generated the least amount of CO_2 emissions rate of 43 g CO_2-eq./kW h because of the relatively higher conversion efficiency. The thin-film Si PV module emitted the most amount of CO_2 emissions rate due to its lower efficiency, more array support materials and more other BOS components needed. Therefore, taking the EPBT and GHG emissions into account, the large scale PV plants using CIS module will achieve the biggest environmental benefits.

LCA review results in [7] showed that the EPBT of mono-Si, multi-Si and a-Si PV systems were estimated to be 3.2–15.5, 1.5–5.7 and 2.5–3.2 years, respectively in previous literatures. Accordingly the GHG emissions rates were in the order of 44–280, 9.4–104 and 15.6–50 g CO_2-eq./kW h, respectively. In addition, this study also pointed out that the EPBT and GHG emissions rate were significantly affected by many parameters, such as irradiation of the location, the types of PV modules, the orientation and tilted angle for installation, installation methods (mounted or integrated, facade or roof-top or ground-mounted), life time of the system, efficiency of the BOS components, and the fuel mix for electricity generation in specific locations. The latest LCA studies from energy and environment viewpoints for PV systems using different solar cells (i.e., mono-Si, multi-Si, a-Si, CdTe and CIS) were conducted by Wild-Scholten [41]. The corresponding EPBT of above PV systems is 1.75, 1.75, 1.4, 0.84 and 1.45 years, respectively, and the corresponding GHG emissions rates were about 30, 29, 24, 16 and 21 g CO_2-eq./kW h, respectively. The above results were stemmed from frameless modules under 1700 kW h/m^2/yr irradiation.

Ito et al. [19] investigated the energy payback and environmental performance of six types of PV modules, viz. mono-Si, multi-Si, a-Si, a-Si/mono-Si, CIS and microcrystalline silicon (μc-Si)/a-Si, with the actual equipment information and energy output results. It was found that the energy requirement of above six types of PV systems ranged from 19 to 48 GJ/kW. The EPBT varied from 1.4 to 3.8 years and CO_2 emission rates between 31 and 67 g CO_2-eq./kW h. Among the six types of PV modules, the CIS and multi-Si PV modules presented better performance from

the viewpoint of environmental benefits because they possessed relatively higher efficiency and lower energy requirement during life cycle. Fthenakis et al. [84] reviewed the previous work in life cycle assessment of PV systems before 2011 and then reported that the latest EPBT of PV systems with roof-top installation were 1.7, 1.7 and 0.8 years for multi-Si, mono-Si and CdTe technologies, respectively, with the solar irradiation of 1700 kW h/m^2/yr. The corresponding GHG emission rate for the above PV technologies were 28, 29 and 18 g CO_2-eq./kW h, respectively. Moreover, with the conversion efficiency raising and the thickness of silicon wafer reducing, the above mentioned EPBT and GHG emission rate still have improve space in future. Cucchiella and D'Adamo [85] estimated the energy and environmental benefits of roof-integrated BIPV systems using different PV technologies, i.e., mono-Si, multi-Si, CdTe and CIS, in Italy. Considering the uncertainty of energy requirement and energy output, the corresponding EPBTs of the above PV systems were 2.4–2.8, 2.5–2.9, 1.8–2.1 and 2.4–2.8 years, respectively. And the corresponding GHG emission rates were 71–84, 72–85, 79–92 and 77–90 g CO_2-eq./kW h, respectively. It was also found that among the four PV technologies, the CdTe PV system had shorter EPBT while mono-Si PV system had less GHG emission rate under the same solar radiation and installation conditions.

5.1. Mono-Si PV system

Mono-Si PV system possesses the highest conversion efficiency among the studied solar cells, but also requires the largest energy requirement during its life cycle. Its energy payback performance was studied as below.

Wilson and Young [86] investigated the energy payback time of two mono-Si PV systems applied in UK buildings in 1996, and concluded that their EPBTs were 7.4–12.1 years for an optimistic scenario without battery bank in an ideal location. The LCA of mono-Si PV system in [35] showed that the EPBT and GHG emission rate for mono-Si PV system was 8.9 years and 61 g CO_2-eq./kW h, respectively under the irradiation of 1427 kW h/m^2/yr. However, if the module production scale expanded from 10 to 100 MW/yr, the energy requirement and CO_2 emission rate would be decreased to two-thirds. Since more energy was required in the form of materials embodied energy rather than the process energy, thus the reduction of glass utilization and the frameless design for the PV module could dramatically decrease the EPBT and GHG emission rates in future. The GHG emission rates of the representative state-of-the-art mono-Si and multi-Si PV power plants in Switzerland ranged from 39 to 110 g CO_2-eq./kW h in 2000. The EPBTs for different PV systems varied from 3 to 6 years [17].

Kannan et al. [87] investigated the EPBT and GHG emission rate of a mono-Si BIPV system in Singapore with actual energy yield. It was found that the EPBT and GHG emission rate of this PV system were 6.74 years and 217 g CO_2-eq./kW h, respectively under the solar radiation of 1635 kW h/m^2/yr. In addition, in order to reduce the energy requirement, three solutions were recommended by the authors, viz. technology improvement in manufacturing PV modules, using alternative material for supporting structure, and increase the PV modules' efficiency. Based on a large amount of actual production data from several manufactures, Fthenakis and Alsema [88] reviewed and updated the PV technology status in 2004 and 2005. The results presented that, under the average South European solar irradiation of 1700 kW h/m^2/yr, the EPBT and GHG emission rate of mono-Si PV system were 2.7 years and 45 g CO_2-eq./kW h, respectively. Some new elements that related to the recycling of sawing slurry and energy consumption in the Czochralski process were updated in [24]. All these two improvements can help reduce energy consumption and GHG emissions for mono-Si PV systems. Thereby, the EPBT of 2.1 years for South-European locations (1700 kW h/m^2/yr) and 3.6 years for Central-European locations (1000 kW h/m^2/yr) could be achieved. The GHG emission rate was about 35 g CO_2-eq./kW h under 1700 kW h/m^2/yr exposure.

García-Valverde et al. [89] studied the energetic performance and environmental impact of a 4.2 kW_p stand-alone mono-Si PV system with life-cycle assessment. The main differences that stand-alone system distinguishing from grid-connected system are that an energy storage system such as a bank of batteries is needed in stand-alone system and its energy output is restricted by the load and the storage capacity of batteries. It is just because of these differences that lead to a higher energy requirement and lower energy production for stand-alone PV system, and consequently result in a longer EPBT of 9.08 years and larger GHG emission rate of 131 g CO_2-eq./kW h. It was found that for a stand-alone system the PV modules and batteries accounted for the vast majority of total energy requirement and GHG emission. In addition, the effects of transportation and recycling on the EPBT and GHG emission rate were estimated and the results showed that they had limited effects on the total embodied energy and GHG emission. A new EPBT calculation method was presented in [90] and was applied to estimate the energy payback time of a stand-alone multi-Si PV system in Greece. The EPBT of stand-alone system ranged from 3.5 to 6 years. Compared with that of grid-connected PV system, the higher EPBT of stand-alone system could be attributed to require a set of batteries for energy storage as well as significant energy surplus during high solar insolation periods.

Table 5 listed the reviewed results of the EPBT of mono-Si PV systems which varying from 1.75 to 12.1 years. The considerable differences were mainly caused by different factors, such as irradiation levels, module efficiencies, types of installations, manufacturing technologies (in particular the source of silicon feedstock), estimation method, and so on. The GHG emission rates were within the range of 30–61 g CO_2-eq./kW h considering different assumptions for energy requirements, local irradiations and life span times.

5.2. Multi-Si PV system

Multi-Si PV system has almost same conversion efficiency as the mono-Si system, but consumes less energy during its life cycle. Therefore, multi-Si maybe has a shorter EPBT and lower GHG emissions rate than mono-Si system.

The EPBT of multi-Si ground-field and roof-top PV systems was estimated to be 3–8 years (under 1700 kW h/m^2/yr irradiation) by Alsema et al.[36], and was expected to be 1.2–2.4 years in future. The life cycle assessment of multi-Si PV systems in Japan showed that the EPBT and GHG emission rate were 2.4 years and 20 g CO_2-eq./kW h respectively with the irradiation of 1427 kW h/m^2/yr [35]. The EPBT and the GHG emission rates of grid-connected PV systems were evaluated in [37]. The EPBTs of multi-Si and a-Si thin film modules were about 2.5–3 years for rooftop systems and 3–4 years for large ground-mounted systems with irradiation of 1700 kW h/m^2/yr. The CO_2 emission rates were in the range of 50–60 g CO_2-eq./kW h. Ito et al. [71] investigated the feasibility to build a 100 MW large-scale PV plant in Gobi Desert of China from both environmental and economic perspectives. The estimated results showed that the EPBT and CO_2 emission rate of this multi-Si PV plant were unbelievably less than 2 years and 12 g CO_2-eq./kW h, respectively. Therefore, considering the generous energy and environment benefits, this large-scale PV plants may be considered as a promising alternative energy source for the Gobi district in future.

Based on the measured data from a number of multi-Si PV manufacturers, Alsema and Wild-Scholten [15] estimated the EBPT and the life-cycle CO_2 emission rates to be 2.2 years and

Table 5
LCA results review of mono-Si PV systems.

No.	Authors/years	Location/irradiation (kW h/m^2/yr)	Module efficiency	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO2-eq./kW he)	Remark
1	Wilson and Young [86]	UK/573–1253	12%	20	0.8	7.4–12.1	N/A	Frame
2	Kato and Murata[35]	Japan/1427	12.2%	20	0.81	8.9	61	The multi-Si and the $SiCl_4$ shared the energy requirement and the CO_2
3	Alsema and Wild-Scholten [59]	South-European/1700	13.7%	30	0.75	2.6	41	Frame
4	Alsema and Wild-Scholten [24]	South-European/1700	14.0%	30	0.75	2.1	35	Frame
5	Jungbluth and Dones [18]	Switzerland/1117	14.0%	30	0.75	3.3	N/A	Slanted-roof, frame, mounted
6	Wild-Scholten [41]	South-European/1700	14.0%	30	0.75	1.75	30	Frameless, on-roof installation
7	Ito and Komoto [73]	China/1702	N/A	N/A	0.78	2.5	50	Very-large scale PV systems installed in desert

35 g CO_2-eq./kW h, respectively with the South-European irradiation of 1700 kW h/m^2/yr. With the latest PV technology status in 2004 and 2005, the EPBT and GHG emission rate of multi-Si PV systems were 2.2 years and 37 g CO_2-eq./kW h, respectively under 1700 kW h/m^2/yr irradiation [88]. Müller et al. [91] studied the recycling processes of end-of-life multi-Si PV modules. Compared with new wafers, a module using recovered wafers from the recycling process would reduce 70% energy input and the corresponding EPBT of module was reduced by 50%, as low as 1.7 years.

Pacca et al. [45] calculated the EPBT and the GHG emission rates of multi-Si PV systems by using process-based LCA methods. The EPBT was 7.5 years with the life-cycle GHG emission rate of 72.4 g CO_2-eq./kW h based on the US electric mix (the GHG emissions rate of US utility grid is about 700 g CO_2-eq./kW h). However, in this study, the energy demand of BOS components was 242 MJ/m^2, and the energy output of multi-Si PV module was 167 kW h/m^2/yr (converted from 155 kW h/0.93 m^2). Therefore, it can be calculated that the EPBT of the BOS components was 0.12 years with considering the electricity conversion efficiency from primary energy to electricity, which was different from the reported results of 0.7 years. The main reason causing the above difference was whether the electricity conversion efficiency from primary energy to electricity is considered or not. Taking this conversion efficiency into account and assuming it is 0.3, the above EPBT of multi-Si systems can be amended from 7.5 to 2.1 years.

Elkem solar silicon (ESS) was a new technology to produce solar-grade silicon and different from the conventional Siemens process. It was found that producing solar-grade silicon by using ESS technology could save 66% energy compared with the conventional Siemens process [77]. Accordingly, the EPBT of rooftop PV system using ESS technology was as short as 1.1 years, which was 0.5 years less than the Siemens process (under the 1700 kW h/m^2/yr irradiation level), and the life-cycle GHG emission rate of whole multi-Si PV system was estimated to be 23 g CO_2-eq./ kW h. Sumper et al. [92] reviewed the previous work focused on the environmental impacts of PV systems and performed a life cycle assessment on a 200 kW roof-top PV system in Spain. It was found that the variation ranges of EPBT and GHG emission rate in previous literature were quite large. The EPBT ranged from 1.7 to 9 years, while the GHG emission rate ranged from 22 to 180 g CO_2-eq./kW h. The authors explained that the big difference in values may attribute to the different boundary settings in each analysis, different electricity mix structure for producing PV modules, and also different production processes and technologies. In addition, a sensitivity analysis about the effect of solar irradiation on the EPBT was conducted by the authors. The results showed that with the solar irradiation increasing from 1408 to 1930 kW h/m^2/yr, the EPBT of multi-Si PV system decrease from 4.94 to 3.67 years.

The EPBT of multi-Si PV systems, as shown in Table 6, varied from 1.7 to 3.3 years. The differences were caused mainly by factors such as solar irradiation, module efficiency and type of installations. The GHG emissions rate is in the order of 12–72 g CO_2-eq./kW h.

5.3. Thin film PV systems

Thin film PV systems have much lower conversion efficiency than crystalline silicon ones, but requires less raw material and less energy during life cycle due to the relatively simple production technologies. Therefore, better EPBT and GHG emission performance are expected.

Srinivas [93] reported that the EPBT of amorphous silicon modules with 5% efficient was about 2.6 years under the solar radiation about 1200 kW h/m^2/yr. However, if the module was not framed with plastic and glass, its EPBT would be reduced to 2.18 years. For the same efficient of module as above, Hagedorn [94] estimated that the EPBT of framed amorphous silicon modules was 3.5 years. Hynes et al. [95] discussed the energy requirement of producing $CuInSe_2$ PV modules with various production technologies and production cases in 1992. The energy requirement was compared for using different technologies for semi-conductor deposition, which including stacked elemental layer processing (SEL), electrodeposition, chemical bath deposition, screen printing and thermal evaporation. In base and best production cases, the energy requirement of different deposition technologies had little difference, but in the worst case, the technology of thermal evaporation would require much more energy. The energy payback time of $CuInSe_2$ modules in three different solar insolation levels was estimated by the authors. The results showed that even with the highest energy requirement, the EPBT was only 11 months for operating in Southern Europe (3 kW h/m^2/day) with conversion efficiency of 10%. If the PV modules operate in Northern Europe and Southwest of USA, the EPBT would be 10–17 and 4–7 months, respectively. In addition, in order to understand which parameters had a major effect on the energy requirement of PV modules, the sensitivity analysis was conducted. It was found that the film deposition rate and the process yields had the highest effect on the total energy requirement of PV producing.

The EPBT for a-Si frame modules with high energy consumption case and low energy consumption case were 8.1 and 4.5 years

Table 6
LCA result review of multi-Si PV systems.

No.	Authors/years	Location/irradiation (kW h/m^2/yr)	Module efficiency	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO_2-eq./kW h_e)	Remark
1	Phylipsen and Alsema [33]	South-European/1700	13%	25	0.75	2.7	N/A	Frame
2	Kato and Murata [35]	Japan/ 1427	11.6%	20	0.81	2.4	20	Frame, 10 MW/yr production scale
3	Alsema [37]	South-European/1700	13%	30	0.75	3.2	60	Frame, roof-top installation
4	Ito and Kato [71]	Gobi Desert of China/1675	12.8%	30	0.78	1.7	12	Large scale PV systems installed in desert
5	Battisti and Corrado [44]	Italy/1530	10.7%	30	0.8	3.3	NA	Frame, flat roof installation
6	Alsema and Wild-Scholten [24]	South-European/1700	13.2%	30	0.75	1.9	32	Frame
7	Pacca and Sivaraman [45]	U.S./1359	12.9%	20	N/A	2.1	72.4/54.6	Frame, 54.6 is for European conditions
8	Jungbluth and Dones [18]	Switzerland/1117	13.2%	30	0.75	2.9	N/A	Frame, slanted-roof mounted
9	Raugei and Bargigli [28]	South-European/1700	14%	20	0.75	2.4	72	Frame, 30% of the material and energy requirements of EG-Si production are allocated to PV
10	Wild-Scholten [41]	South-European/1700	13.2%	30	0.75	1.75	29	Frameless, on-roof installation
11	Ito and Komoto [73]	China/1702	N/A	N/A	0.78	2.0	43	Very-large scale PV systems installed in desert

respectively in 1997 (with the irradiation of 1974 kW h/m^2/yr and cell conversion efficiency of 5%) [56]. However, if the PV modules were frameless, the EPBT would accordingly further reduce to 3.7 and 3.0 years, respectively as the frame accounted for 40–50% of the energy consumption in the a-Si module production. It was reported that for cadmium telluride thin film modules, the production process and the disposal/decommissioning stage had the most potential to result in severe environmental pollution [96]. Nieuwlaar and Alsema [9] performed studies on energy analysis of thin-film (a-Si and CdTe) PV modules, and pointed out that the EPTB of frameless modules was below 2 years in the technology state of 1997 (under the irradiation of 1700 kW h/m^2/yr). Adding one more frame can increase the EPTB of thin film PV modules by 0.6 years. The encapsulation materials and the direct processing energy contributed to the major part of the energy consumption for thin film modules. Hynes et al. [97] conducted life cycle analysis on two types of cadmium telluride (CdTe) thin film modules which using different deposition technologies for the absorber and window layers. One type of module used chemical bath deposition and electrodeposition for window and absorber layers, respectively (type 1). The other one used thermal evaporation deposition for these layers (type 2). The energy requirements and EPBT for these two types of CdTe modules were analyzed. The results showed that the total energy requirements for type 1 and type 2 were 992.52 and 1187.7 MJ/m^2 ,[5] respectively. The corresponding EPBTs of the above CdTe modules (10% conversion efficiency) were 5–11 and 6–13 months, respectively, depending on different solar insolation level.

The EPBT and GHG emission rate of a-Si PV system were estimated to be 2.1 years and 17 g CO_2-eq./kW h respectively under the irradiation of 1427 kW h/m^2/yr in [35]. It also mentioned that the energy requirement and CO_2 emission rate would be decreased further with the module production scale expansion. Alsema [50] estimated the EPBT of a grid-connected system using a-Si or CdTe thin film modules, and the results were below 2 years with 1700 kW h/m^2/yr irradiation. However, the utilization of aluminum frame might increase the EPBT by 0.3 to 0.6 years. Pacca et al. [45] calculated the EPBT and the GHG emission rate of a-Si thin film PV systems by using process-based LCA methods. The EPBT of a-Si thin film systems was found to be 3.2 years, and the life-cycle GHG emission rate was 34.3 g CO_2-eq./kW h. However, the electricity conversion efficiency from primary energy to electricity wasn't considered by the authors. If this conversion efficiency was considered with a value of 0.3, the above EPBT of a-Si system was estimated to be 1.1 years.

An empirical investigation on the manufacturing of PV modules showed that the EPBTs of crystalline silicon module and CIS thin film module were found to be 4.1 and 2.2 years, respectively [38]. In other words, the energy yield ratio (EYR) of CIS module was about 14. The effects of BOS components on the EPBT were also discussed. When heavy support structures or batteries were used, the EBPT would remarkably increase by 0.8 years due to the use of high energy intensity materials such as aluminum. The life-cycle analysis on CdS/CdTe thin-film PV modules under three different production scales, i.e., 10, 30 and 100 MW, was performed in [29]. The results showed that the EPBT of a roof-top residential PV system using the CdS/CdTe PV modules ranged from 1.7 (10 MW/yr scale) to 1.1 years (100 MW/yr), and the life-cycle CO_2 emission rate varied from 14 (10 MW/yr) to 9 g CO_2-eq./kW h (100 MW/yr). Ito et al. [51] conducted a comparative study from the energy and environment perspectives for large-scale PV plants by using four types of PV modules, namely multi-Si, a-Si, CdTe and CIS modules. The EPBT and CO_2 emission rate were evaluated. For the multi-Si PV systems, the EPBTs were 1.9 and 1.5 years with different module efficiencies of 12.8 and 15.8%. The EPBTs for other thin film PV systems, i.e., a-Si, CdTe and CIS modules, were 2.5, 1.9 and 1.6 years, respectively. The total life cycle GHG emission was 14,842 g CO_2-eq./m2 for the CIS, 13,451 g CO_2-eq./m2 for CdTe, 14,789 g CO_2-eq./m2 for a-Si and 31,009 g CO_2-eq./m2 for multi-Si modules. Accordingly, the CO_2 emission rates of multi-Si PV systems were 12.1 and 9.4 g CO_2-eq./kW h in correspondence with the module efficiencies of 12.8 and 15.8%. For other thin film modules including a-Si, CdTe and CIS, their CO_2 emission rates were 15.6, 12.8 and 10.5 g CO_2-eq./kW h, respectively.

[5] 992.52 MJ/m^2 and 1187.7 MJ/m^2 are converted in terms of 275.7 and 329.92 kW h(th)/m^2, respectively.

Fthenakis and Kim [12] firstly conducted the life cycle analysis on CdTe thin film PV module based on the real materials and energy data from manufacture plant. The reported EPBT and GHG emission rate of CdTe PV module were around 0.75 years and 18 g CO_2-eq./kW h, respectively with assumed conversion efficiency of 9%, solar radiation of 1800 kW h/m^2/yr and system performance ratio of 0.8. Given the adoption of the state-of-the-art BOS components, the EPBT and GHG emission rate of CdTe PV system would increase to 1.2 years and 23.6 g CO_2-eq./kW h, respectively. The EPBT of thin film PV systems such as CdTe, a-Si and CIS were reported in [24], which ranged from 1–1.5 years (1700 kW h/m^2/yr), and their GHG emissions rates were around 25 g CO_2-eq./kW h. With the same solar irradiation, the EPBT and GHG emission rate of CdTe PV system were estimated to be 1.1 years and 25 g CO_2-eq./kW h, respectively under the technology status in 2004 and 2005 [88]. However, these estimates were not the lowest for CdTe PV modules. Based on the data obtained from Antec Solar in Germany, Raugei et al. [28] conducted a thorough energy and environment analysis for CdTe and CIS thin film PV modules. The results showed that the EPBT of CdTe and CIS PV modules were only 0.5 and 1.9 years, and their life-cycle GHG emission rates were 17 and 70 g CO_2-eq./kW h, respectively. However, if the BOS components were taken into account, the above four figures would become 1.5 and 2.8 years, and 48 and 95 g CO_2-eq./kW h. The latest LCA energy requirement and GHG emissions results for CdTe PV module was updated in [98]. Depending on the installation location, the GHG emission and EPBT of CdTe PV system ranged from 19–30 g CO_2-eq./kW h and 0.7–1.1 years, respectively. The potential environmental benefits of the material recycling and energy recovery for CdTe PV system were investigated for the first time. The result showed that the GHG emissions and energy requirement would be reduced to about 2.5 kg CO_2-eq./m^2 and 12.5 MJ/m^2, respectively by energy recovery from waste incineration of plastics and recycling glass cullet, wires, and copper from the junction box.

The reviewed LCA results for thin film PV modules are shown in Tables 7–9, respectively. It is found that the reviewed EPBT for thin film PV systems varied from 0.7 to 3.2 years, and the GHG emission rate is in the order of 10.5–95 g CO_2-eq./kW h. The considerable differences are caused by the types of modules (frame or frameless) and manufacturing technologies.

Although a-Si thin film PV module needs less energy requirement during life cycle, its EPBT and GHG emission rate appear to be higher than that of crystalline silicon PV modules due to its lower conversion efficiency and consequently higher BOS requirement, such as requirements of more module frame, array supports, and so on.

In order to compare the energy benefits and environmental impact of different PV technologies, the review results of EPBT and GHG emission rate of the studied 5 PV technologies are presented in Figs. 5 and 6, respectively. With the same reason for Fig. 4 (see Section 3.3.2), only literature after 2005 are considered in summarizing the EPBT and GHG emission rate of crystalline silicon PV systems. Moreover, all results in these two figures are normalized with the same solar radiation of 1700 kW h/m^2/yr, which was used by previous scholars. From these two figures, it is found that the CdTe PV system has the shortest EPBT and the least GHG emission rate while the mono-Si and a-Si PV systems have the worst performance due to their

Table 7
LCA result review of a-Si PV systems.

No.	Authors/years	Location/ irradiation (kW h/m^2/yr)	Module efficiency	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO_2-eq./kW h_e)	Remarks
1	Lewis and Keoleian [56]	USA/1974	5%	25	N/A	3.0	N/A	Frameless, low energy consumption case
2	Alsema [50]	NW-European/1000	6%	N/A	0.75	3.2	N/A	Frame
3	Alsema [37]	South-European/1700	7%	30	0.75	2.7	50	Frame
4	Jungbluth and Dones [18]	Switzerland/1117	6.5%	30	0.75	3.1	N/A	Frame, slanted-roof mounted
5	Pacca and Sivaraman [45]	U.S./1359	6.3%	20	N/A	3.2	34.3	Frame
6	Ito and Kato [51]	China/2017	6.9%	30	0.81	2.5	15.6	Frame, 100 MW very large-scale PV plant
7	Wild-Scholten [41]	South-European/1700	6.6%	30	0.75	1.4	24	Frameless, on-roof installation

Table 8
LCA result review of CdTe PV systems.

No.	Authors/years	Location/irradiation (kW h/m^2/yr)	Module efficiency	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO_2-eq./kW h_e)	Remarks
1	Alsema [50]	NW-European/1000	6%	N/A	0.75	3.2	N/A	Frame
2	Kato [29]	Japan/1430	10.3	20	0.81	1.7	14	Frame, 10 MW production scale
3	Fthenakis and Kim [12]	U.S./1800	9%	30	0.80	1.2	23.6	Frameless
4	Alsema and Wild-Scholten [24]	South-European/1700	9%	30	0.75	1.1	25	Ground-mount system, U.S. production, frameless
5	Jungbluth and Dones 2007 [18]	Switzerland/1117	7.1%	30	0.75	2.5	N/A	Frameless, slanted-roof, integrated
6	Raugei and Bargigli [28]	South-European/1700	9%	20	0.75	1.5	48	Frame
7	Wild-Scholten [41]	South-European/1700	10.9%	30	0.75	0.84	16	Frameless, on-roof installation
8	Fthenakis [99]	South-European/1700	10.9%	N/A	0.8	0.79	18	Ground mounted module
9	Ito and Komoto [73]	China/1702	N/A	N/A	0.78	2.1	50	Very-large scale PV systems installed in desert
10	Held [100]	Europe/1200–1700	10.9%	30	0.8	0.7–1.1	19–30	Ground mounted module

Table 9
LCA result review of CIS PV systems.

No.	Authors/years	Location/irradiation ($kW h/m^2/yr$)	Module efficiency	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO_2-eq./kW h_e)	Remarks
1	Jungbluth and Dones [18]	Switzerland/1117	10.7%	30	0.75	2.9	N/A	Frame, slanted-roof mounted
2	Raugei and Bargigli [28]	South-European/1700	11%	20	0.75	2.8	95	Frame
3	Ito and Kato [51]	China/2017	11%	30	N/A	1.6	10.5	Frame, 100 MW Very Large-scale PV
4	Wild-Scholten [41]	South-European/1700	10.5%	30	0.75	1.45	21	Frameless, on-roof installation
5	Ito and Komoto 2010 [73]	China/1702	11%	N/A	0.78	1.8	46	Very-large scale PV systems installed in desert

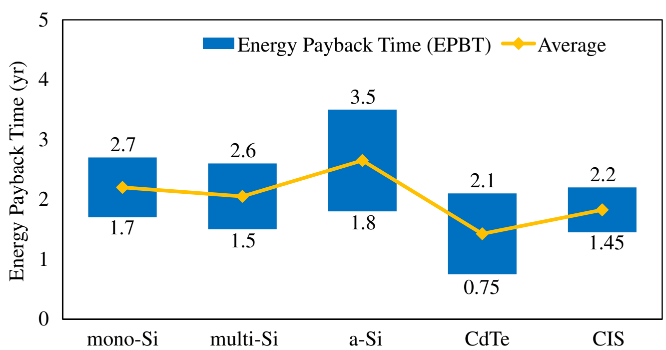


Fig. 5. Review of energy payback time for various PV systems.

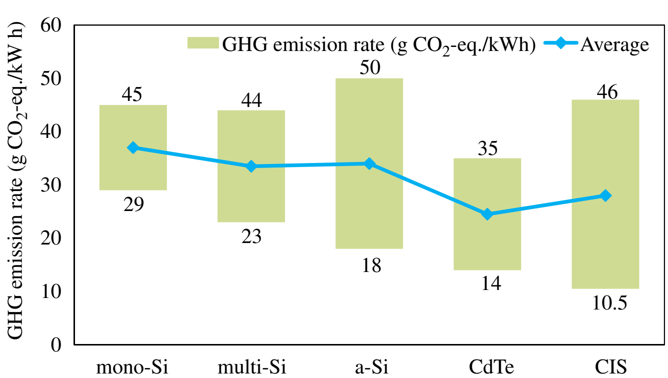


Fig. 6. Review of GHG emission rates of PV electricity generated by various PV systems.

large energy requirements in life cycle and low energy conversion efficiency, respectively.

5.4. EPBT and GHG emission of balance of system (BOS)

Investigating the EPBT and GHG emission of the BOS of PV system is very important, especially for thin film PV system because the BOS account for relatively high proportion in its total energy requirement.

Mason et al. [54] conducted life-cycle analysis for the BOS components in a 3.5 MW_p multi-Si PV plant. The on-site measured EPBT of the BOS was 0.21 years under irradiation of 2100 $kW h/m^2/yr$, which was a great improvement compared with 1.3 years in an older plant. For the environmental impact, the life-cycle GHG emission of BOS components was also reduced to 29 kg CO_2-eq./m^2, which could be converted into 6 g CO_2-eq./kW h with the irradiation of 1700 $kW h/m^2/yr$ and 8 g CO_2-eq./kW h with South Germany insolation of 1300 $kW h/m^2/yr$ [88]. Through this typical PV system, we can conclude that the EBPT and GHG emission rate of BOS components may drop dramatically when the system design is optimized. The EPBT and GHG emissions rate of CdTe PV system were reported to be 1.9 years and 53 g CO_2-eq./kW h, respectively in [72], to which the BOS components contributed 1.0 years of EPBT and 21 g CO_2-eq./kW h. Therefore, if the effects stemmed from BOS components could be improved by reducing the possible amount of aluminum and steel used in the support structure, the EBPT and GHG emissions rate of CdTe PV system might sharply decrease.

Wild-Scholten et al. [25] investigated the environmental impacts of roof-top and ground-based crystalline silicon PV systems by using life cycle assessment methodology. The results showed that GHG emission rate of BOS components (not including frame) used in multi-Si PV systems was about 1.8 to 4 g CO_2-eq./kW h. But, if the module frame was added, particularly for the ground-based mounting systems, the GHG emissions rate would greatly increase to 6–9.5 g CO_2-eq./kW h. This additional GHG emission was caused by the large amount of aluminum and steel used in the mounting systems. The total GHG emission rate for multi-Si PV systems (including PV module and BOS components) were in the range of 33–41 g CO_2-eq./kW h. For an in-roof PV system, the GHG emissions of BOS components can be negligible (as low as 3% of the total emissions). But for the on-roof systems or ground-based systems, the GHG emissions of BOS components (including frame) accounted for 16–23% of the total emissions of the PV systems.

5.5. EPBT and GHG emission of other PV systems

High-concentration PV systems, characterized with the merits of less energy used and higher conversion efficiency, are getting increasingly popular in recent years. At the same time, their energy payback and environmental performances were also evaluated.

Peharz and Dimroth [101] evaluated the ecological benefits and the sustainability of FLATCON high-concentration PV systems, which used III–V multi-junction solar cells with 500 times Fresnel lenses concentration rate. The main components accounting for energy requirement of FLATCON system in descending order were trackers, modules, cells, transportation, cellchips and BOS. The estimated EPBT of this system was about 0.7–0.8 years with the irradiation of 1900 $kW h/m^2/yr$ in Tabernas of Spain, and 1–1.3 years for system installed in Germany. Obviously, this low EPBT is attributed to higher efficiency of multi junction III–V solar cells and high concentration rate. The environmental benefits of a 24 kW Amonix concentrator PV system was evaluated by Kim and Fthenakis in 2006 [8]. The life cycle primary energy input and GHG emissions of this system were 817 GJ and 56,000 kg CO_2-eq., respectively. The EPBT and GHG emission rate of this PV system were 1.3 years and 38 g CO_2-eq./kW h under the irradiation of 2480 $kW h/m^2/yr$ in Phoenix, Arizona. Different from the

common PV systems in which most of energy was used and emissions were generated during the production process of the solar PV modules, the frames and tracker were the main source of energy consumption and GHG emissions in this case. Wild-Scholten et al. [102] reported that the EPBT and GHG emission rates of Concentrator PV systems, which were installed in Sicily of Italy, ranged from 0.8–1.9 years and 18–45 g CO_2-eq./kW h, respectively depending on tracking modes and materials using.

The LCA analysis for SolFocus concentrator PV system was conducted in [103]. Unlike the common flat PV systems, in which the main energy consumption is attributed to cell and module manufacturing, the optical concentrator accounted for the most part of energy consumption for this concentrator PV system. In addition, the transportation energy also contributed 25% of the total energy requirement for producing this PV system. It was found that the EPBTs of a SolFocus PV system installed in Pheonix and Berkeley were 1.3 and 1.5 years, respectively, which are close to the ones of thin film PV technologies such as CIS and CdTe. Furthermore, the measures, such as reducing transportation energy consumption and replacing energy intensive materials (particularly aluminum) with recycled materials, were recommended to further reduce the concentrator PV system's EPBT. Nishimura et al. [1] investigated the environmental impact and EPBT of high-concentration PV (hcPV) systems installed in Toyohashi of Japan and Gobi Desert of China respectively by LCA methodology. The results showed that the total environmental impacts of hcPV system installed in Toyohashi were higher than those in Gobi desert by 5% without considering recycling. The cumulated energy demand of hcPV system installed in Toyohashi and Gobi desert was 5.76×106 and 5.15×106 kJ, respectively with less support material for Gobi Desert than that for Toyohashi. Consequently, the EPBTs of hcPV systems in Toyohashi and Gobi desert were 2.64 and 2.0 years, respectively. In addition, the comparisons between hcPV systems and multi-Si PV systems in terms of environmental impact and EPBT were conducted. The total environmental impacts of hcPV systems were about two times bigger than those of multi-Si PV systems. The higher environmental impacts of hcPV were mainly attributed to the tracking system manufacturing, which accounted for 68.1 to 71.8% of the total impacts of hcPV systems. The EPBTs of multi-Si PV systems and hcPV systems was 1.73 and 2.0 years respectively under the irradiation of 1701 kW h/m^2/yr in Gobi Desert, which could be partly explained that multi-Si PV systems had a lower cumulated energy demand and were able to utilize the global solar radiation while hcPV could only utilize the direct beam solar radiation. Therefore, multi-Si PV systems were better than hcPV systems in Gobi Desert in terms of environmental-friendly and EPBT.

Olson et al. [104] conducted a life cycle assessment on heterojunction cells and made a comparison with standard mono-Si cells in terms of EPBT and GHG emission rate. Actually, the energy requirement and GHG emission during life cycle was quite approximate for the above kinds of solar cells. However, because the heterojunction cells had higher conversion efficiency (16.4%) than that of mono-Si solar cells (14%), thus their environmental performance in terms of EPBT and GHG emission rate was better than that of mono-Si solar cells. The EPBT and GHG emission rate of heterojunction cells were 1.2 years and 20 g CO_2-eq./kW h, respectively with the solar radiation of 1700 kW h/m^2/yr. In addition, the specific energy requirement in each manufacture process for both types of solar cells was estimated by the authors.

A life cycle assessment on environmental burden of flexible amorphous silicon/nano-crystalline silicon (a-Si/nc-Si) PV system was presented in [105]. This flexible laminate consists of two tandem solar cells, viz. the a-Si cell lie on the top and the nc-Si cell lie on the bottom. With 10% conversion efficiency, the EPBT of this a-Si/nc-Si PV system was about 2.3 years under the solar radiation of 1000 kW h/m^2/yr, which was less than that of multi-Si PV system by 1.1 years. The energy requirement and environmental impact in each stage of manufacturing was analyzed in depth for a-Si/nc-Si solar laminate. The results showed that the process of constructing roof integration contributes the largest energy demand, and then followed by deposition a-Si/nc-Si layer and etching. For the environmental impact, the process of encapsulation and constructing roof integration are the two largest pollutant sources.

As dye-sensitized solar cells with low costs becoming promising recently, their environmental performance will also be examined. Kato et al. [106] evaluated the CO_2 emission reduction effects of dye-sensitized solar cells by life cycle assessment. It was found that the CO_2 emission rate of dye-sensitized solar cells with different cases ranged from 84.5 to 393 g CO_2/kW h, and the corresponding CO_2 payback time was between 4.92 and 27.9 years with 1200 kW h/m^2/yr irradiation. From these results, we can find that the dye-sensitized solar cells are not yet better than other common solar cells in terms of GHG emission reduction at the moment, but may be potentially better with the emerging of new technology and enhanced efficiency in the future.

6. New technologies and measures and their effects on EPBT and GHG emission rate

The new technologies and measures which can help to reduce the life cycle energy requirement of PV systems are summarized as below.

As early as 2000, it was already presented that if new technologies, such as dedicated silicon feedstock production for PV applications, improving casting methods and reducing silicon requirements, were achieved, the energy requirements of multi-Si and mono-Si modules were expected to reach as low as 2600 and 3200 MJ/m^2, respectively [37]. A number of important options to further reduce energy consumption and environment impacts during the crystalline silicon PV module production processes was reviewed and reported in [46]. The proposed options included introducing new silicon feedstock processes, reducing silicon consumption, increasing energy-efficiency in ingot growing, recycling SiC slurry, enhancing energy-efficiency in cell processing and module assembly, and effectively recycling module materials in the end-of-life. Compared with the Siemens reactors, the new silicon feedstock processes of Fluidized Bed Reactors would reduce 570 MJ primary energy for producing 1 kg of poly-Si. If the silicon kerf loss could be recycled, the silicon consumption would be substantially reduced by 30–40%. The recycling of Sic slurry could decrease the wafer energy requirement by 15%, and recycling aluminum frame could help reduce 192 MJ/kg primary energy. In addition, reusing and recovering silicon wafers from waste module could save 75% energy on a module level. Fthenakis [107] analyzed the sustainability of thin-film modules from the viewpoints of direct costs, resource availability, and environmental impacts. It was found that reducing the thickness of solar cells and effectively recycling the modules at the end of their useful life would be crucial for resolving the problems of costs, resources, and environmental impacts to achieve a considerable sustainable growth. Improvements in the traditional Siemens process, such as using fluidized bed reactor to replace the rods, was reported to could reduce the energy requirement from 999 to 788 kW h/m^2 [108]. And the GHG emissions were accordingly expected to reduce from 21 to 17 g/kW h.

Given the complexity of the PV systems and the using of large amount of materials, simplified life cycle analysis was conducted by Frankl et al. [58]. Through examining previous applications and

conducting parametric analysis for possible improvements in the BOS components, the authors found that compared with conventional PV power plants in open fields the main advantages of building-integrated PV systems are the saving of construction materials (energy consumption of BOS could be reduced by 50 to 66% for BIPV systems), the substitution of building envelope materials and the possibility of recovering a significant fraction of the thermal energy dissipated by PV modules. These benefits supported the feasibility of using PV modules to replace conventional building envelope materials and to recover the thermal energy dissipated by PV modules. The EPBTs of mono-Si PV systems with various installation methods ranged from 4 to 12 years with the least for BIPV system combined with a heat recovery unit. The dual-effects of the heat recovery system, namely heat recovery and cooling down cell temperature for achieving higher cell efficiency, can help further reduce the EBPT of a tilted roof-top PV system with thermal energy recovery to half of the EBPT of PV power plant. In order to enhance the overall energy efficiency of PV systems, a solution of recovering thermal energy from module was considered in [44]. This can not only improve the electrical output efficiency (by decreasing the higher module temperature), but also provide available thermal energy for utilization. For different installation cases, the evaluated EPBT was in the range of 2.9–3.8 years. If the thermal energy recovered from module was considered, the EPBT would be cut down by 50%. Therefore, introducing the heat recovery may greatly increase the environmental-friendly of PV systems. Oliver and Jackson [109] also illustrated the advantages of BIPV systems by comparing the respective costs of electricity from a BIPV cladding system, a centralized PV plant and a conventional electricity supply mix. For generating per kW h power, the primary energy needed for conventional electricity supply, the centralized PV plant and the BIPV system was 13.2, 4.15 and 2.9 MJ, respectively. If the energy embodied in a glass cladding system was deducted from the energy requirement of BIPV system due to the substitution of this conventional cladding material with PV models, the embodied energy of BIPV system would be reduced to 2.6 MJ/kW h. Therefore, taking into account the energy saving achieved by displacing conventional cladding materials, the merits of BIPV system will be more distinct. Merits can also be reflected in terms of EPBTs, the EPBTs of centralized PV plants and BIPV cladding systems were around 8 and 4.75 years respectively with the average annual energy output of 850 kW h/kW_p.

The electricity mix used in manufacturing PV modules may have an important effect on the environmental impacts of PV systems, in particular the GHG emission rate of PV electricity. Using renewable energy, such as hydro power, wind power and solar energy, for PV module manufacturing could significantly reduce the environmental harm [110]. Pacca et al. [45] pointed out that by replacing conventional electricity with PV generation electricity for PV modules' manufacturing, the GHG emission rates for multi-Si and a-Si PV systems could be reduced by 68 and 82%, respectively. The environmental performance of GaInP/GaAs thin-film PV module and multi-Si module manufactured by PV generated electricity was assessed in [111]. When PV electricity is used to substitute for conventional fossil electricity in the life cycle of each PV module, the total environmental impacts of GaInP/GaAs module and multi-Si module would be reduced to one fifth and two fifth, respectively. The GaInP/GaAs module would obtain much more environmental benefits than the multi-Si module when fossil electricity is totally replaced by PV electricity. It was also reported that the GHG emission rates of multi-Si and CdTe PV systems would be reduced by 6 and 2 g/kW h, respectively if replacing 30% of the total conventional electricity by PV electricity during the production processes [21]. Reich et al. [112] investigated the variation of GHG emissions of crystalline silicon module under different electricity supply options during the whole PV module production chain. The total GHG emissions generated during the whole life cycle were separated into two parts, namely direct emissions and indirect emissions. The direct emissions were mainly stemmed from the silicon feedstock production, the fluorinated process gases release and the incineration of plastics in the recycle stage. The indirect emissions were mainly attributed to the electricity-input during the production processes. It was found that the choice of electricity supply technologies would have large influence on the indirect GHG emissions. Indirect emissions related to the electricity-input could vary from 0 to 200 g CO_2-eq./kW h depending on the different electricity supply technologies, such as coal-fired, natural gas, wind power, hydropower, and PV power. While the direct emissions only contributed about 1–2 g CO_2-eq./kW h.

7. Discussions and conclusions

The life cycle assessment of five common types PV systems (say mono-Si, multi-Si, a-Si, CdTe thin film, and CIS thin film) and some advanced solar cells systems (such as high-concentration PV, heterojunction solar cells and dye-sensitized solar cells) were discussed in terms of energy requirement, energy payback time and GHG emission rate during whole life cycle. The findings are summarized as below:

1) The reported values of primary energy requirement, EPBT and GHG emission rates of different PV systems vary significantly from case to case due to the variation of influencing factors, such as solar cell type, module type, manufacturing processes and technologies, installation methods and locations, location weather conditions, estimation methods, etc.
2) For mono-Si PV systems, there was a considerable variance among previous studies. Life cycle energy requirement ranged from 2860 to 5253 MJ/m^2, and EPBTs varied from 1.7 to 2.7 years. These differences were mainly stemmed from the energy estimation for silicon purification and crystallization processes. The GHG emission rate was in the order of 29–45 g CO_2-eq./kW h, which was about an order of magnitude smaller than that of fossil-based electricity.
3) For multi-Si PV system, the cumulated energy requirement was estimated to be 2699–5150 MJ/m^2. The EPBT and GHG emission rate were 1.5–2.6 years and 23–44 g CO_2-eq./kW h, respectively.
4) For thin film PV systems (a-Si, CdTe and CIS), the life cycle total energy input ranged from 710 to 1990 MJ/m^2. Consequently, the EPBT and GHG emission rate were within the range of 0.75–3.5 years and 10.5–50 g CO_2-eq./kW h, respectively. Among the three thin film PV systems, the CIS consumed the largest amount of primary energy, and the a-Si had the longest EPBT due to its lower conversion efficiency. CdTe possessed the shortest EPBT and the lowest environmental impacts.
5) For advanced PV systems (high-concentration system and dye-sensitized system), the EPBT and GHG emission rate were also reviewed. The EBPT of high-concentration PV system ranged from 0.7 to 2.0 years, which was almost equivalent to the thin film PV technologies of CIS and CdTe. However, at the moment, the CO_2 emission rate of dye-sensitized PV system was a little higher than those of other common PV systems, but was expected to own a better environmental performance with emerging new technologies and enhanced efficiency in the near future.
6) In general, mono-Si PV systems had the highest life cycle energy requirement, while thin film PV systems (especially CdTe and a-Si systems) had the lowest energy demand. For EPBT, the CdTe PV system had the shortest EPBT due to its lower energy demand and relatively high conversion efficiency. Meanwhile, although the energy requirement of a-Si

PV system was lower, its high EPBT can be attributed to the extremely low conversion efficiency. In the aspect of GHG emission rate, mono-Si would generate more GHG emissions during its life cycle because of the high energy intensity of solar cells production processes.

7) New technologies and measures, such as new silicon feedstock production processes, improving casting method, recycling of SiC slurry and module materials, reducing the thickness of solar cells and other raw materials consumption, BIPV technologies, PV-T technologies, etc., can help to further lower the life cycle energy requirement and significantly reduce the environmental impacts of PV systems.
8) There are also some limitations in previous research, such as considerable differences in the estimation of energy requirement, inaccurate estimation of direct process energy and material embodied energy, using annual total solar irradiation instead of hourly radiation data, simplifying power output estimation by using simplified equations, etc. All these limitations would finally result in a noticeable uncertainty in estimating the EPBT and GHG emission rate of PV systems. Therefore, further research is recommended to obtain more accurate results.

In a word, PV technologies are proved to be sustainable and environmental-friendly regarding the measured EPBT and GHG emission rate. Amongst the five common types of solar cells, CdTe thin film PV technologies give the best environmental benefits such as the shortest of EPBT and the least of GHG emission rate due to its lower life cycle energy demand and relatively higher conversion efficiency, while silicon-based PV systems perform the worst environmental benefits considering their energy and environmental impacts during life cycle, especially mono-Si PV due to its high energy intensity of solar cells production processes. These results are in line with the other review study [85,113]. In addition, advanced PV systems (high-concentration, heterojunction and dye-sensitized PV systems) also demonstrate good environmental performance.

Many factors will affect the estimation results of life cycle energy requirement, EPBT and GHG emission rate of PV systems. However, new manufacturing technologies and application methods, such as advanced production processes, reducing silicon and other raw materials consumption, increasing material recycling rates, and building-integrated PV technologies, PV-thermal technologies, will further reduce the estimation values and improve the environmental performance of PV systems in the near future.

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References

[1] Nishimura A, Hayashi Y, Tanaka K, Hirota M, Kato S, Ito M, et al. Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system. Applied Energy 2010;87:2797–807.
[2] ISO 14040. Environmental management – life cycle assessment – principles and framework; 1997.
[3] ISO 14041. Environmental management – life cycle assessment – goal and scope definition and inventory analysis; 1998.
[4] ISO 14042. Environmental management – life cycle assessment – life cycle impact assessment; 2000.
[5] ISO 14043. Environmental management – life cycle assessment – life cycle interpretation; 2000.
[6] Jungbluth N. Life cycle assessment of crystalline photovoltaics in the Swiss ecoinvent database. Progress in Photovoltaics Application and Research 2005;13(5):429–46.
[7] Sherwani AF, Usmani JA, Varun. Life cycle assessment of solar PV based electricity generation systems: a review. Renewable and Sustainable Energy Reviews 2010;14:540–4.
[8] Kim, HC, Fthenakis, VM. Life cycle energy demand and greenhouse gas emissions from an amonix high concentrator photovoltaic system. In: Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion; 2006. pp. 628–631.
[9] Nieuwlaar, E, Alsema, E. Environmental aspects of PV power systems. IEA PVPS Task 1 Workshop. Utrecht, The Netherlands, 25–27 June, 1997.
[10] Fthenakis VM, Moskowitz PD. Photovoltaics: environmental, health and safety issues and perspectives. Progress in Photovoltaics: Research and Applications 2000;8:27–38.
[11] Meier PJ, Kulcinski GL. Life-cycle energy requirements and greenhouse gas emissions for building-integrated photovoltaics. Madison, USA: Fusion Technology Institute, University of Wisconsin; 2002.
[12] Fthenakis, VM, Kim, HC Energy use and greenhouse gas emissions in the life cycle of thin film CdTe photovoltaics. In: Proceedings of Symposium G-Life Cycle Analysis, Materials Research Society Fall Meeting. Boston, Nov. 29–Dec 2. 2005.
[13] Alsema, E, Fraile, D, Frischknecht, R, Fthenakis, V, Held, M, Kim, HC, et al. Methodology guidelines on life cycle assessment of photovoltaic electricity. IEA PVPS Task 12, Subtask 20, LCA Report, October 2009.
[14] Fthenakis V, Frischknecht R, Raugei M, Kim HC, Alsema E, Held M, et al. Methodology guidelines on life cycle assessment of photovoltaic electricity. 2nd ed. IEA PVPS Task 12, International Energy Agency Photovoltaic Power systems Programme.
[15] Alsema, EA, Wild-Scholten, MJ. Environmental impacts of crystalline silicon photovoltaic module production. In: Proceedings of Materials Research Society Fall Meeting. Boston, Nov. 29-Dec 2. 2005.
[16] Dones R, Frischknecht R. Life-cycle assessment of photovoltaic systems: results of swiss studies on energy chains. Progress in Photovoltaics Research and Applications 1998;6:117–25.
[17] Jungbluth N, Bauer C, Dones R, Frischknecht R. Life cycle assessment for emerging technologies: case studies for photovoltaic and wind power. International Journal of LCA 2005;10(1):24–34.
[18] Jungbluth, N, Dones, R, Frischknecht, R. Life cycle assessment of photovoltaics; update of the ecoinvent database. In: 14th SETAC LCA Case Studies Symposium. Giteborg, 2007. 〈www.esu-services.ch/fileadmin/download/jungbluth-2007-PV-MRSpdf〉.
[19] Ito M, Kudo M, Nagura M, Kurokawa K. A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant. Progress in Photovoltaics Research and Applications 2011;19:878–86.
[20] Aulich HA, Schulze F. Crystalline silicon feedstock for solar cells. Progress in Photovoltaics Research and Applications 2002;10:141–7.
[21] Fthenakis VM, Kim HC, Alsema E. Emissions from photovoltaic life cycles. Environmental Science & Technology 2008;42(6):2168–74.
[22] Bernreuter J. Full stream ahead. Sun & Wind Energy 2006;2006(2):92ff.
[23] Jungbluth, N, Stucki, M, Frischknecht, R. (2009) Photovoltaics. In Dones, R , et al, editors, Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. ecoinvent report No. 6-XII, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, 2009. 〈http://db.ecoinvent.org/ecoquery/files/06_XII_Photovoltaics_v2.1.pdf?area=463ee7e58cbf8〉.
[24] Alsema, EA, Wild-Scholten, MJ, Fthenakis, VM. Environmental impacts of PV electricity generation—a critical comparison of energy supply options. In: Proceedings of 21th European Photovoltaic Solar Energy Conference. Dresden, Germany, 4–8 September 2006.
[25] Wild-Scholten, MJ, Alsema, EA, Horst, EW, Bächler, M, Fthenakis, VM. A cost and environmental impact comparison of grid-connected rooftop and ground-based PV systems. In: Proceedings of 21th European Photovoltaic Solar Energy Conference. Dresden, Germany, 4–8 September 2006.
[26] Wild-Scholten, MJ, Alsema, EA. Environmental life cycle inventory of crystalline silicon photovoltaic system production: status 2005/2006. (Download from 〈http://www.ecn.nl/docs/library/report/2007/e07026-LCI data-cSiPV-pubv2_0.xls〉).
[27] Shell Solar (2000) Homepage Shell Solar Deutschland retrieved from: 〈www.shell.com/de-de/〉.
[28] Raugei M, Bargigli S, Ulgiati S. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy 2007;32:1310–8.
[29] Kato K, Hibino T, Komoto K, et al. A life-cycle analysis on thin-film CdS/CdTe PV modules. Solar Energy Materials & Solar Cells 2001;67:279–87.
[30] Hunt, LP Total energy use in the production of silicon solar cells from raw materials to finished product. In: Photovoltaic Specialists Conference. 12th, Baton Rouge, La., November 15–18; 1976.
[31] Palz W, Zibetta H. Energy pay-back time of photovoltaic modules. International Journal of Solar Energy 1991;10(3–4):211–6.
[32] Schaefer H, Hagedorn G. Hidden energy and correlated environmental characteristics of PV power generation. Renewable Energy 1992;2(2):159–66.

[33] Phylipsen, GJM, Alsema, EA. Environmental life-cycle assessment of multi-crystalline silicon solar cell modules. Report No. 95057. Utrecht, Netherlands: Department of Science, Technology and Society, Utrecht University; 1995.
[34] Prakash R, Bansal NK. Energy analysis of solar photovoltaic module production in India. Energy Sources 1995;17:605–13.
[35] Kato K, Murata A, Sakuta K. Energy pay-back time and life-cycle CO_2 emission of residential PV power system with silicon PV module. Progress in Photovoltaics Research and Applications 1998;6:105–15.
[36] Alsema, EA, Frankl, P, Kato, K. Energy pay-back time of photovoltaic energy systems: present status and prospects. In: Presented at the 2nd World Conference on Photovoltaic Solar Energy Conversion. Vienna, 6–10 July 1998.
[37] Alsema EA. Energy pay-back time and CO_2 emissions of PV systems. Progress in Photovoltaics Research and Applications 2000;8:17–25.
[38] Knapp K, Jester T. Empirical investigation of the energy payback time for photovoltaic modules. Solar Energy 2001;71(3):165–72.
[39] Knapp, K, Jester, T. Initial empirical results for the energy payback time of photovoltaic modules. In: Proceedings of the 16th European Photovoltaic Solar Energy Conference. Glasgow, UK, May 1–5, 2000.
[40] Nawaz I, Tiwari GN. Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level. Energy Policy 2006;34:3144–52.
[41] Wild-Scholten, MJ. Energy payback times of PV modules and systems. In: Workshop Photovoltaik-Modultechnik. Köln, 26–27 November 2009.
[42] Laleman R, Albrecht J, Dewulf J. Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. Renewable and Sustainable Energy Reviews 2011;15:267–81.
[43] Alsema EA, Nieuwlaar E. Energy viability of photovoltaic systems. Energy Policy 2000;28:999–1010.
[44] Battisti R, Corrado R. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. Energy 2005;30:952–67.
[45] Pacca S, Sivaraman D, Keoleian GA. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 2007;35: 3316–26.
[46] Alsema, EA, Wild-Scholten, MJ. Reduction of the environmental impacts in crystalline silicon module manufacturing. In: Proceedings of the 22nd European Photovoltaic Solar Energy Conference and Exhibition. Milan Italy, 2007; p. 829–836.
[47] Lewis, G, Keoleian, GA. Amorphous silicon photovoltaic modules: a life cycle design case study. In: IEEE International Symposium on Electronics and the Environment. Dallas, 1996, p. 141–7.
[48] Lewis, G, Keoleian, G. Life cycle design of amorphous silicon photovoltaics modules. EPA/600/SR-97/081, October 1997.
[49] Keoleian GA, Lewis GM. Application of life-cycle energy analysis to photovoltaic module design. Progress in Photovoltaics: Research and Applications 1997;5:287–300.
[50] Alsema EA. Energy requirements of thin film solar cell modules—a review. Renewable and Sustainable Energy Reviews 1998;2:387–415.
[51] Ito M, Kato K, Komoto K, Kichimi T, Kurokava K. A comparative study on cost and life-cycle analysis for 100 MW very large-scale (VLS-PV) systems in deserts using m-Si, a-Si CdTe and CIS modules. Progress in Photovoltaics Research and Applications 2008;16:17–30.
[52] Ito, M, Kudo, M, Kurokawa, K. A preliminary life-cycle analysis of a mega-solar system in Japan. In: Proceedings of PVSEC-17. 2007; p. 508–511.
[53] Alsema, EA. Energy requirements and CO2 mitigation potential of PV systems. In: BNL/NREL Workshop, PV and the Environment 1998. Keystone, CO, USA, July 23–24, 1988. BNL-52557. Brookhaven National Laboratory: Upton, NY.
[54] Mason JM, Fthenakis VM, Hensen T, Kim HC. Energy payback and life-cycle CO_2 emissions of the BOS in an optimized 3.5 MW PV installation. Progress in Photovoltaic Research and Applications 2006;14(2):179–90.
[55] Alsema, EA, Wild-Scholten, MJ. Environmental impacts of crystalline silicon photovoltaic module production. In: Presented at 13th CIRP International Conference on Life Cycle Engineering. Leuven, 31 May–2 June 2006.
[56] Lewis, G, Keoleian, G. Life cycle design of amorphous silicon photovoltaics modules. APE/600/SR-97/081, October 1997.
[57] Perpirpis O, Lorenzo E, Castro MA, Eyras R. Energy payback time of grid connected PV systems: comparison between tracking and fixed systems. Progress in Photovoltaic Research and Applications 2009;17:137–47.
[58] Frankl P, Masini A, Gamberale M, Toccaceli D. Simplified life-cycle analysis of PV systems in buildings: present situation and future trends. Progress in Photovoltaics Research and Applications 1998;6:137–46.
[59] Alsema, EA, Wild-Scholten, MJ. The real environmental impacts of crystalline silicon PV modules: an analysis based on up-to-date manufacture data. In: Proceedings of the 20th European Photovoltaic Solar Energy Conference. Barcelona, 6–10 June, 2005.
[60] 〈http://eosweb.larc.nasa.gov/sse/RETScreen/〉.
[61] Perez R, Ineichen P, Seals R. Modeling of daylight availability and irradiance components from direct and global irradiance. Solar Energy 1990;44(5): 271–89.
[62] Perez R, Seals R, Ineichen P, Stewart R, Menicucci D. A new simplified version of the Perez diffuse irradiance model for tilted surfaces. Solar Energy 1987;39(3):221–31.
[63] Hay, JE, Davies, JA. Calculation of the solar radiation incident on an inclined surface. In: Proceeding of First Canadian Solar Radiation Data Workshop.- Toronto, 1979, p. 59–72.
[64] Reindl DT, Beckman WA, Duffie JA. Evaluation of hourly tilted surface radiation models. Solar Energy 1990;45(1):9–17.
[65] Li DHW. Cheung GHW. Study of models for predicting the diffuse irradiance on inclined surfaces. Applied Energy 2005;81(2):170–86.
[66] Lu, L. Investigation on characteristics and application of hybrid solar-wind power generation systems. Ph.D Dissertation, The Hong Kong Polytechnic University; 2004.
[67] Cheng, KP. Energy payback time and greenhouse gas emission analysis of a roof-mounted BIPV in Hong Kong. MEng. Dissertation. The Hong Kong Polytechnic University; 2008.
[68] Lu L, Yang HX. Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. Applied Energy 2010;87:3625–31.
[69] Alsema EA, Wild-Scholten MJ. Environmental impacts of crystalline silicon photovoltaic module production. Materials Research Society Symposium Proceedings 2006;895(G03-05):1–9.
[70] Paula Sanchez-Friera Michel, Piliougine Javier Pelaez, Carretero J, Cardona MS. Analysis of degradation mechanisms of crystalline silicon PV modules after 12 years of operation in Southern Europe. Progress in Photovoltaic Research and Applications 2011;19:658–66.
[71] Ito M, Kato K, Sugihara H, Kichimi T, Song J, Kurokava K. A preliminary study on potential for very large-scale photovoltaic power generation (VLS-PV) system in the Gobi desert from economic and environmental viewpoints. Solar Energy Materials & Solar Cells 2003;75:507–17.
[72] Raugei, M, Bargigli, S, Ulgiati, S. Energy and life cycle assessment of thin film CdTe photovoltaic modules. In: Proceedings of the 20th European Photovoltaic Solar Energy Conference. 2005; p.1886–1889.
[73] Ito M, Komoto K, Kurokawa K. Life-cycle analyses of very-large scale PV systems using six types of PV modules. Current Applied Physics 2010;10:S271–3.
[74] Kato K, Murata A, Sakuta K. An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon. Solar Energy Materials & Solar Cells 1997;47:95–100.
[75] Jahn U, Nasse W. Operational performance of grid-connected PV systems on buildings in Germany. Progress in Photovoltaics Research and Applications 2004;12(6):441–8.
[76] Annual Energy Review 2003. Energy Information Administration, DOE/EIA-0384, 2003. (Download from 〈http://www.eia.doe.gov/aer〉).
[77] Gløckner, R, Odden, JO, Halvorsen, G, Tronstad, R, Wild-Scholten, MJ. Environmental life cycle assessment of the Elkem solar metallurgical process route to solar grade silicon with focus on energy consumption and greenhouse gas emissions. Silicon for the Chemical and Solar Industry IX. Oslo, Norway, June 23–26, 2008.
[78] Stoppato A. Life cycle assessment of photovoltaic electricity generation. Energy 2008;33:224–32.
[79] De Soto W, Klein SA, Beckman WA. Improvement and validation of a model for photovoltaic array performance. Solar Energy 2006;80(1): 78–88.
[80] Nieuwlaar E, Alsema E. PV power systems and the environment: results of an expert workshop. Progress in Photovoltaics: Research and Applications 1998;6:87–90.
[81] Komiyama H, Yamada K, Inaba A, Kato K. Life cycle analysis of solar cell systems as a means to reduce atmospheric carbon dioxide emissions. Energy Conversion and Management 1996;37:1247–52.
[82] Fthenakis VM, Kim HC. Greenhouse-gas emissions from solar electric- and nuclear power: a life-cycle study. Energy Policy 2007;35:2549–57.
[83] Jungbluth, N, Tuchschmid, M, De Wild-Scholten, M. Life cycle assessment of photovoltaics: update of ecoinvent data v2.0. Working paper; 2008. (〈http://esu-services.ch/fileadmin/download/jungbluth-2008-LCA-PV-web.pdf〉).
[84] Fthenakis, V, Kim, HC, Frischknecht, R, Raugei, M, Sinha, P, Stucki, M. Life cycle inventories and life cycle assessment of photovoltaic systems. International Energy Agency (IEA) PVPS Task 12, Report T12-02:2011.
[85] Cucchiella F, D'Adamo I. Estimation of the energetic and environmental impacts of a roof-mounted building-integrated photovoltaic systems. Renewable and Sustainable Energy Reviews 2012;16:5245–59.
[86] Wilson R, Young A. The embodied energy payback period of photovoltaic installations applied to buildings in the UK. Building and Environment 1996;31(4):299–305.
[87] Kannan R, Leong KC, Osman R, Ho HK, Tso CP. Life cycle assessment study of solar PV systems: An example of a 2.7 kW_p distributed solar PV system in Singapore. Solar Energy 2006;80:555–63.
[88] Fthenakis VM, Alsema EA. Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status. Progress in Photovoltaics Research and Applications 2006;14:275–80.
[89] García-Valverde R, Miguel C, Martínez-Béjar R, Urbina A. Life cycle assessment study of a 4.2 kW_p stand-alone photovoltaic system. Solar Energy 2009;83:1434–45.
[90] Kaldellis JK, Zafirakis D, Kondili E. Energy pay-back period analysis of stand-alone photovoltaic systems. Renewable Energy 2010;35:1444–54.
[91] Müller, A, Wambach, K, Alsema, EA. Life cycle analysis of solar module recycling process. In: Materials Research Society Symposium Proceedings 2006; 895: 0895/G03/07.1- 0895/G03/07.6.
[92] Sumper A, Robledo-García M, Villafáfila-Robles R, Bergas-Jané J, Andrés-Peiró J. Life-cycle assessment of a photovoltaic system in Catalonia (Spain). Renewable and Sustainable Energy Reviews 2011;15:3888–96.

[93] Srinivas KS. Energy investments and production costs of amorphous silicon PV modules. Bern: Swiss Federal Department of Energy; 1991.
[94] Hagedorn, G. Hidden energy in solar cells and photovoltaic power stations. In: Ninth EC Photovoltaic Solar Energy Conference. Freiburg, FRG, 25 September. Boston: Kluwer, 1989; p. 542–545.
[95] Hynes, KM, Pearsall, NM, Hill, R. The sensitivity of energy requirements to process parameters for CuInSe2 module production. In: 22nd IEEE PV Specialists Conference. Las Vegas, NV, Vol. 1 (1992); p. 822–927.
[96] Hynes, KM, Baumann, AE, Hill, R. Life cycle analysis of PV modules based on cadmium telluride. In: 12th EC PVSEC. 1994; p. 309–312.
[97] Hynes, KM, Baumann, AE, Hill, R. An assessment of the environmental impacts of thin film Cadmium Telluride Modules based on life cycle analysis. In: Presented at the IEEE 1st World Conference on Photovoltaic Conversion (WCPEC). HI, 1994; p. 958–961.
[98] Held M, Ilg R. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. Progress in Photovoltaic Research and Applications 2011;19:614–26.
[99] Fthenakis, V, Kim, HC, Held, M, Raugei, M, Krones, J. Update of PV energy payback times and life-cycle greenhouse gas emissions. In: 24th European Photovoltaic Solar Energy Conference. 21–25 September 2009, Hamburg, Germany.
[100] Held M, Ilg R. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. Progress in Photovoltaics: Research and Applications 2011;19:614–26.
[101] Peharz G, Dimroth F. Energy payback time of the high-concentration PV System FLATCON. Progress in Photovoltaics Research and Applications 2005;13:627–34.
[102] De Wild-Scholten, M, Sturm, M, Butturi, MA, Noack, M, Heasman, K, Timò, G. Environmental sustainability of concentrator PV systems: preliminary LCA results of the APOLLON project. In: 5th World Conference on Photovoltaic Energy Conversion Valencia. Spain, 6–10 September 2010.
[103] Minassians, AD, Farshchi, R, Nelson, J, Weiser, CR, Zhang, T. Energy payback time of a SolFocus Gen1 concentrator PV system. Final Project Report (MSE-ER C226 - Photovoltaic Materials); December 7, 2006.
[104] Olson, C, de Wild-Scholten, M, Scherff, M, Ribeyron, PJ. Life cycle assessment of heterojunction solar cells and modules. In: 26th European Photovoltaic Solar Energy Conference and Exhibition. 5–9 September 2011, Hamburg, Germany.
[105] Mohr, NJ, Meijer, A, Huijbregts, MAJ, Reijnders, L. Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate. Progress in Photovoltaics: Research and Applications 2012. (http://dx.doi.org/10.1002/pip.2157).
[106] Kato T, Yoshiie R, Uemiya S, et al. Evaluation of CO_2 reduction effect of dye-sensitized solar cell by LCA. Journal of the Japan Institute of Energy 2007;86:978–86.
[107] Fthenakis VM. Sustainability of photovoltaics: the case for thin-film solar cells. Renewable and Sustainable Energy Reviews 2009;13:2746–50.
[108] Jiao YB, Salce A, Ben W, Jiang F, Ji XY, Morey E, et al. Siemens and siemens-like processes for producing photovoltaics: energy payback time and lifetime carbon emissions. Journal of the Minerals Metals and Materials Society 2011;63(1):28–31.
[109] Oliver M, Jackson T. Energy and economic evaluation of building-integrated photovoltaics. Energy 2001;26:431–9.
[110] Beloin-Saint-Pierre, D, Blanc, I, Payet, J, Jacquin, P, Adra, N, Mayer, D. Environmental impact of PV systems: effects of energy sources used in production of solar panels. In: Proceedings of the 24th European Photovoltaïc Solar Energy Conference. 21–25 September 2009, Hamburg, Germany.
[111] Mohr N, Meijer A, Huijbregts MA. Environmental impact of thin-film GaInP/GaAs and multicrystalline silicon solar modules produced with solar electricity. International Journal of LCA 2009;14:225–35.
[112] Reich NH, Alsema EA, Van Sark WGJHM, Turkenburg WC, Sinke WC. Greenhouse gas emissions associated with photovoltaic electricity from crystalline silicon modules under various energy supply options. Progress in Photovoltaic Research and Applications 2011;19:603–13.
[113] Fthenakis VM, Kim HC. Photovoltaics: life-cycle analyses. Solar Energy 2011;85:1609–28.